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CHARACTERISATION OF NORTH ATLANTIC RIGHT WHALE (*EUBALEANA GLACIALIS*) UNDERWATER VOCALISATIONS RECORDED IN THE BAY OF FUNDY, JULY 1999

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Defence R&D Canada

Contractor Report

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CHARACTERISATION OF NORTH ATLANTIC RIGHT WHALE (*EUBALEANA GLACIALIS*) UNDERWATER VOCALISATIONS RECORDED IN THE BAY OF FUNDY, JULY 1999

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Abstract

Hydrophone recordings made in the presence of a North Atlantic right whale (*Eubalaena glacialis*) aggregation in July 1999 provide data for part of a pilot study to assess the feasibility of a passive acoustic whale monitoring and locating system. Digitised vocalisations are quantified in the time and frequency domains to classify the vocalisations in terms of frequency, modulation, duration, harmonics, and time between individual vocalisations. The majority of the mean fundamental frequencies range between 340 and 600 Hz and on average the duration of the vocalisations was 0.42 seconds + 0.26s SD. Right whale vocalisations are frequency and amplitude modulated and a 95% confidence interval for modulation relative to the mean fundamental frequency is [-0.82 0.46]. Harmonics and non-harmonic frequency bands above the fundamental were seen in 27% of the vocalisations and may not be significant characteristics in terms of monitoring. Vocalisations occur at a rate of 0.32 to 0.69 per minute, suggesting that North Atlantic right whales are vocalizing sufficiently for monitoring. The vocalisations of North Atlantic right whales contain distinct characteristics that are detectable and can be quantified to allow for automated monitoring of right whales in the Bay of Fundy.

Résumé

Des enregistrements faits par hydrophone en présence d'un groupe de baleines noires de l'Atlantique Nord (*Eubalaena glacialis*) en 1999 fournissent des données pour un volet d'un projet pilote visant à évaluer la faisabilité d'un système acoustique passif de surveillance et de repérage des baleines. Les vocalisations numérisées sont quantifiées dans les domaines temporel et fréquentiel pour classer ces vocalisations en termes de fréquence, de modulation, de durée, d'harmonique et de temps entre chaque vocalisation. La gamme de la plupart des fréquences fondamentales moyennes s'étendait de 340 à 600 Hz, et la durée moyenne des vocalisations était de 0,42 ± 0,26 (écart-type) secondes. Les vocalisations des baleines noires comportaient des modulations de fréquence et d'amplitude; l'intervalle de confiance à 95 % de la modulation par rapport à la fréquence fondamentale moyenne s'étendait de -0,82 à 0,46. Vingt-sept pour cent des vocalisations présentaient des bandes de fréquences harmoniques et non harmoniques supérieures à la fréquence fondamentale; ces bandes ne constituent peut-être pas des caractéristiques importantes pour la surveillance. Les vocalisations se produisaient à un taux de 0,32 à 0,69 par minute, ce qui porte à croire que les baleines noires de l'Atlantique Nord vocalisent suffisamment pour faire l'objet d'une surveillance acoustique. Les vocalisations des baleines noires de l'Atlantique Nord présentent des caractéristiques détectables et quantifiables qui permettent la surveillance automatisée de ces baleines dans la baie de Fundy.

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Executive Summary

There has been increasing public and governmental concern about the potential harm to whales resulting from acoustically-intense naval exercises (e.g. low-frequency active sonar experiments) as well as live-fire exercises. Heightened concern was recently triggered by whale stranding incidents that closely followed naval exercises in May 1996 in the Ionian Sea and in March 2000 in the Bahamas. Furthermore, collisions between naval and/or commercial vessels are a known cause of mortality among marine mammals. The particular focus of this report is the North Atlantic right whale (*Eubalaena glacialis*), which is a highly endangered species with a critically low population size. Collisions with large vessels are the greatest single contributor to the documented cases of recent anthropogenic mortalities in this species. Shipping lanes to the major commercial and naval ports on the eastern seaboard of North America intersect primary migratory routes and winter and summer habitat areas of the North Atlantic right whale.

Real-time knowledge of whale locations relative to naval operational areas and naval traffic zones is a fundamental requirement for minimising the risks of collision and of the effects of noise. Passive acoustic monitoring of whale vocalisations may prove to be the easiest, most efficient, and safest (minimal risk) manner to localise and monitor (track) whales in or near an operational area or traffic zone. To this end, a pilot study was conducted in 1999 in the Bay of Fundy in the presence of a North Atlantic right whale aggregation. The study was designed as a preliminary assessment of the feasibility of using passive acoustics for whale monitoring and location. The first step of the pilot study resulted in quantitative characterisation of whale vocalisations in terms of frequency, modulation, duration, harmonics, and time between individual vocalisations. These results are summarised in this report.

The majority of the observed mean fundamental frequencies of the vocalisations observed during the 1999 pilot experiment ranged between 340 and 600 Hz, with average durations of 0.42 seconds ± 0.26s sd. The observed vocalisations were frequency and amplitude modulated and a 95% confidence interval for modulation relative to the mean fundamental frequency was [-0.08 0.05]. Harmonics and non-harmonic frequency bands above the fundamental were observed in 27% of the vocalisations. Vocalisations occurred at a rate of 0.3 to 0.7 per minute. These results are comparable to previously published observations of Southern right whale (*Eubalaena australis*) vocalisations, and the small number of available results for the Northern right whale.

It is concluded from this pilot study that, in the North Atlantic right whale summer/fall nursery area (the Grand Manan Basin in the Bay of Fundy), the vocalisations are sufficiently frequent and recognisable that further investigation of the potential of passive acoustic tracking and monitoring is worthwhile. This study further indicates that the vocalisations of North Atlantic right whales contain distinct characteristics that are

suitable for automated detection and monitoring in this area, indicating the feasibility in principle of a real-time tracking system.

Sommaire

On se préoccupe de plus en plus, tant dans le grand public qu'au gouvernement, du danger potentiel que représentent pour les cétacés les opérations navales à forte intensité acoustique (comme les expériences sur le sonar actif à basse fréquence) et les exercices de tir réel. Les préoccupations se sont accentuées suite à des échouages de baleines survenus juste après des opérations navales en mer Ionienne (mai 1996) et aux Bahamas (mars 2000). De plus, les collisions avec des bâtiments des forces navales ou de la marine marchande sont une cause connue de mortalité chez les mammifères marins. Ce rapport vise particulièrement la baleine noire, ou baleine franche boréale, (*Eubalaena glacialis*), espèce en péril dont l'effectif est dangereusement bas. Les collisions avec de gros bateaux constituent le premier facteur responsable des mortalités d'origine anthropique observées chez cette espèce. Les routes maritimes qui mènent aux principaux ports militaires et commerciaux de la façade orientale de l'Amérique du Nord coupent les principales voies migratoires et les habitats d'hivernage et d'estivage de la baleine noire.

Si l'on veut réduire au minimum les risques de collision et les dangers d'ordre acoustique, il importe de connaître en temps réel la position des baleines par rapport aux zones d'opérations navales et de trafic maritime. La surveillance acoustique passive des vocalisations des cétacés pourrait se révéler la méthode la plus facile, la plus efficace et la plus sûre (risque minimal) pour localiser et surveiller (pister) les baleines près des zones opérationnelles ou des voies maritimes. À cette fin, une étude pilote a été menée en 1999 dans la baie de Fundy en présence d'un troupeau de baleines noires. L'étude représentait une évaluation préliminaire de l'intérêt de l'acoustique passive pour surveiller et localiser les baleines. La première étape de l'étude a fourni une caractérisation quantitative des vocalisations des cétacés en termes de fréquence, de modulation, de durée, d'harmoniques et d'intervalles entre les vocalisations des individus. Le présent rapport résume les résultats obtenus.

La majorité des fréquences fondamentales moyennes des vocalisations observées pendant l'expérience pilote de 1999 se situaient entre 340 et 600 Hz, avec des durées moyennes de 0,42 s ± 0,26 s ET. Les vocalisations observées étaient modulées en fréquence et en amplitude, et l'intervalle de confiance à 95 % pour la modulation par rapport à la fréquence fondamentale moyenne était [-0,08 , 0,05]. Des harmoniques et des bandes de fréquences non harmoniques ont été observées au-dessus de la fréquence fondamentale dans 27 % des vocalisations. Ces vocalisations se produisaient au rythme de 0,3 à 0,7 par minute. Ces résultats sont comparables à ceux d'observations publiées sur les vocalisations de la baleine franche australe (*Eubalaena australis*), et à la maigre information dont on dispose sur la baleine noire.

L'étude pilote permet de conclure que, dans la pouponnière d'été/automne de la baleine noire (bassin de Grand Manan, dans la baie de Fundy), les vocalisations sont

assez fréquentes et reconnaissables pour justifier la poursuite des essais sur le pistage et la surveillance acoustique passive. L'étude révèle en outre que les vocalisations des baleines noires présentent des caractéristiques particulières qui se prêtent bien à la détection et à la surveillance automatisées dans cette région, résultat qui montre la faisabilité de principe d'un système de pistage en temps réel.

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Technical Summary

The North Atlantic right whale (*Eubalaena glacialis*) is an endangered species and the critically low population size in eastern North America has focussed preservation initiatives. Human-related mortalities result from ship collisions and fishing gear entanglements. Between 1970 and 1999, ~36% of the documented mortality resulted from ship collision and many other animals bear scars from the same. As the whales inhabit the Bay of Fundy during summer and autumn in a region that overlaps a shipping lane, the probability of collision is enhanced. Contemporary techniques for warning ships include regular aerial and vessel surveys. However, these are restricted by high cost and logistical limitations and are confounded by visibility, observer bias, and our poor understanding of whale behaviour. More efficient and cost-effective methods for tracking right whales in real-time might be used to reduce the collision probability. Real time acoustic tracking using a fixed array of hydrophones could reduce collision probability and provide quantitative information on abundance, distribution, migration patterns, and behaviour.

Hydrophone recordings made in the presence of a right whale aggregation on 29 July 1999 on the RV *Nereid* and simultaneous recordings from an array of 16 sonobuoys, provided data for a pilot study testing the real-time passive acoustic tracking concept. This report focuses on the hydrophone recordings. Digitised and filtered vocalisations were assessed in the time and frequency domains to classify the vocalisation frequency, modulation, duration, harmonic structure, and time between vocalisations (clustering).

Using the two hours of data from the ship-based hydrophone, 53 vocalisations were identified. The majority of these vocalisations occurred in a frequency band between 340 to 600 Hz. A small proportion of the vocalisations occurred with fundamental frequencies below 150 Hz. Another small proportion of vocalisations was observed with mean fundamental frequencies above 900 Hz and one vocalisation with a mean fundamental frequency as high as 1536 Hz was observed. Vocalisations were generally narrow-band sounds with frequency modulation in the form of upsweeps, downsweeps, or a combination of the two. With ± 20% representing the greatest change in frequency relative to the mean fundamental frequency, the interval [-0.082 0.046] characterises 95% of the observed frequency variation relative to the mean fundamental frequency. On average, the vocalisations lasted just under half a second with the duration ranging from 0.08 to 1.26 s. Amplitude modulation was also observed in recordings. Both frequency and amplitude modulation, as well as the presence of harmonics and (possibly) non-harmonic frequency bands contribute to the complex structure of the North Atlantic right whale vocalisations.

The acoustic records also demonstrated a clustering of vocalisations. If the probability of a vocalisation was small and occurred in a random fashion it might be reasonable to expect the time-on-track for the vocalisations to follow a Poisson distribution. Evidence from this study clearly illustrates this is not the case. As many as

9 vocalisations per minute were identified in the hydrophone recordings and the average time-between-vocalisations was 73.4 s (median = 19.5 s, mode = 3 s) and the longest waiting time for a vocalisation was 1013 s. Clusters were defined as vocalisations occurring within 15 seconds of the previous vocalisation. Eleven such clusters were found in the data, ranging in size from 2 to 5 vocalisations per cluster.

Although the number of right whales vocalising is not known there are indications that more than one whale was vocalising during the hydrophone recordings. Vocalisations within clusters have previously been thought to be attributed to a single animal. However, intensity levels two orders of magnitude greater than other vocalisations were observed within the same cluster. This pattern is suggestive of multiple individuals making concurrent vocalisations.

Noise, caused by the method of hydrophone deployment, was a factor in these analyses. The highest amplitude noise was characterised by broadband "gurgling", lasting typically 0.1 s. Noise amplitude increased on average towards lower frequencies. Although steps were taken to reduce the effects of noise in this study, including the electronically filtering of signals below 100 Hz prior to digitisation, there were still occasions where the vocalisations were masked at least partially by noise. All vocalisations were initially identified aurally and when the recordings were digitised an event marker (voltage pulse) was recorded on a separate channel. This was important for locating each vocalisation in the spectra, as they were not always distinct due to the broadband noise caused by the deployment method of the hydrophone.

Once the vocalisations were detected in the spectrograms, a "box" was defined around each vocalisation allowing for the isolation of a small segment of the spectrograms. Much of the noise was eliminated from the analysis by the restriction of this "box". Despite these efforts, vocalisations may still have been masked by noise. Within these vocalisations which were detected, noise likely had greatest impact on the calculation of vocalisation duration. When noise appeared, it could prematurely shorten our perception of the vocalisation or even divide one vocalisation into two.

There were instances in the recordings for which the intensity[λ] of a particular vocalisation was very low and the vocalisation was not evident in the spectrogram, but could be identified aurally. The inability to identify a vocalisation in the spectrogram may have been either from the greater intensity of noise or the distance of the vocalising whale relative to the hydrophone. To acquire an estimate of the frequency of such a vocalisation, digital bandpass (low and high) filtering was executed in increments of 100 Hz and the filtered signal replayed until an estimate of the vocalisation's fundamental frequency was obtained.

These recordings are quite similar to those that have been reported for the Southern right whales, although Northern right whales appear to have a wider frequency range than Southern right whales. The Southern right whale vocalisations (fundamental

[λ] The acoustic intensities and spectral densities reported here are uncalibrated, and are reported in units of $Volts^2$ and $Volts^2/Hz$ respectively. Calibrations are being applied to the data as part of ongoing work

frequencies) are generally below 500 Hz whereas Northern right whales recorded here produced sounds where the majority of the energy of the fundamental frequency was between 300 and 600 Hz. Payne and Payne (1971) noted Southern right whales having vocalisations as high as 1500 Hz, which has also been observed in this data set for the North Atlantic right whale.

The data from this study are similar to the first recording of North Atlantic right whales published by Schevill and Watkins (1964). The up-sweeping contact calls between 80-250 Hz identified by Clark (1999), were not observed in this study, however due to the noise intensities at these frequencies, they may have been missed. Spectral comparisons between our *in-situ* hydrophone and an on-whale hydrophone (Johnson, Nowacek, and Tyack, unpublished data) are also generally similar.

The fundamental frequency and duration appear to be useful characteristics for the identification of right whale vocalisations in a system to give advanced warning of right whale presence to approaching vessels. Duration estimates may help to eliminate non-whale sounds detected by an early warning system. Those that are within the same frequency range as the right whale vocalisation but several standard deviations away from the mean duration may not be important. The presence of frequency bands above the fundamental may not be a crucial characteristic for detecting and identifying right whales, as few vocalisations demonstrated this characteristic in these recordings. However, the wide range of fundamental frequencies suggest that acquisition of signals at frequencies up to 2000 Hz could be useful, in which case harmonics would be detected in many instances. These vocalisations contain distinct characteristics that are detectable and can be quantified to allow for monitoring of right whales in the Bay of Fundy and illustrate the potential for a fixed array of hydrophones for real-time tracking. Such a system could be used to reduce the collision probability and fishing gear conflicts as well as provide quantitative information on abundance, distribution, migration patterns, and behaviour.

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Abbreviations and Symbols

BOF	Bay of Fundy
dB	decibel
DREA	Defence Research Establishment, Atlantic
f_*	approximate peak frequency
f_m	frequency of maximum intensity
f_p	peak frequency
G_n	Greenwood statistic
G_{obs}	Observed Greenwood statistic
Hz	hertz
i_t	time interval between vocalisations
k	number of vocalisations in an interval
kHz	kilohertz
MLE	maximum likelihood estimate
ms	millisecond
m	sample size
NB	New Brunswick
NEAq	New England Aquarium
N_k	observed number of intervals containing k vocalisations
N_p	expected number of intervals containing k vocalisations
NS	Nova Scotia
s	second
SAG	surface active group
SD	standard deviation
t	time
t_1	time-on-track of the first vocalisation
t_i	time-on-track
WHOI	Woods Hole Oceanographic Institute

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1. INTRODUCTION

The North Atlantic right whale (*Eubalaena glacialis*) is the most endangered large whale species in the world (Kenney *et al*., 1994, Hamilton *et al*., 1998,Caswell *et al*., 1999) Historically this species was targeted early by whalers and earned the name of "right whale" because it was the easiest whale to kill - they were slow swimmers, were found in coastal areas, floated when dead, and provided large quantities of oil and whale bone. Hunted as early as the ninth and tenth centuries by the Basques and Norwegians, the species was brought to commercial extinction by 1750 (Allen, 1908).

1.1 Population Size

Kenney and his colleagues (1994) estimated the population of the North Atlantic right whale to be between 2 to 173 animals in 1935 using annual growth rate back-calculations Genetic studies also indicate very low population sizes as there were only three matrilines (line of descent as traced through the maternal side) found among 47% of the contemporary population (Schaeff *et al*., 1992). There are now no more than 350 individuals in the North Atlantic (Anon, 1999). Over the last decade the population growth rate has decreased and was significantly lower than the South Atlantic right whale (*Eubalaena australis*; Knowlton *et al*., 1994). As of 1994, the population intrinsic growth rate for North Atlantic right whale is less that one, i.e. the species is in negative growth (Caswell *et al*., 1999). Under prevailing conditions of high anthropogenic mortality and concomitant decreased survival probability, the species has an estimated time to extinction of ≈ 200 years (Caswell *et al*., 1999).

1.2 Distribution

The North Atlantic right whale is migratory (Figure 1.1.1) and ranges throughout the lower latitude temperate waters in the western North Atlantic in the winter months and moves to higher latitude temperate waters in the summer months (Gaskin, 1991).

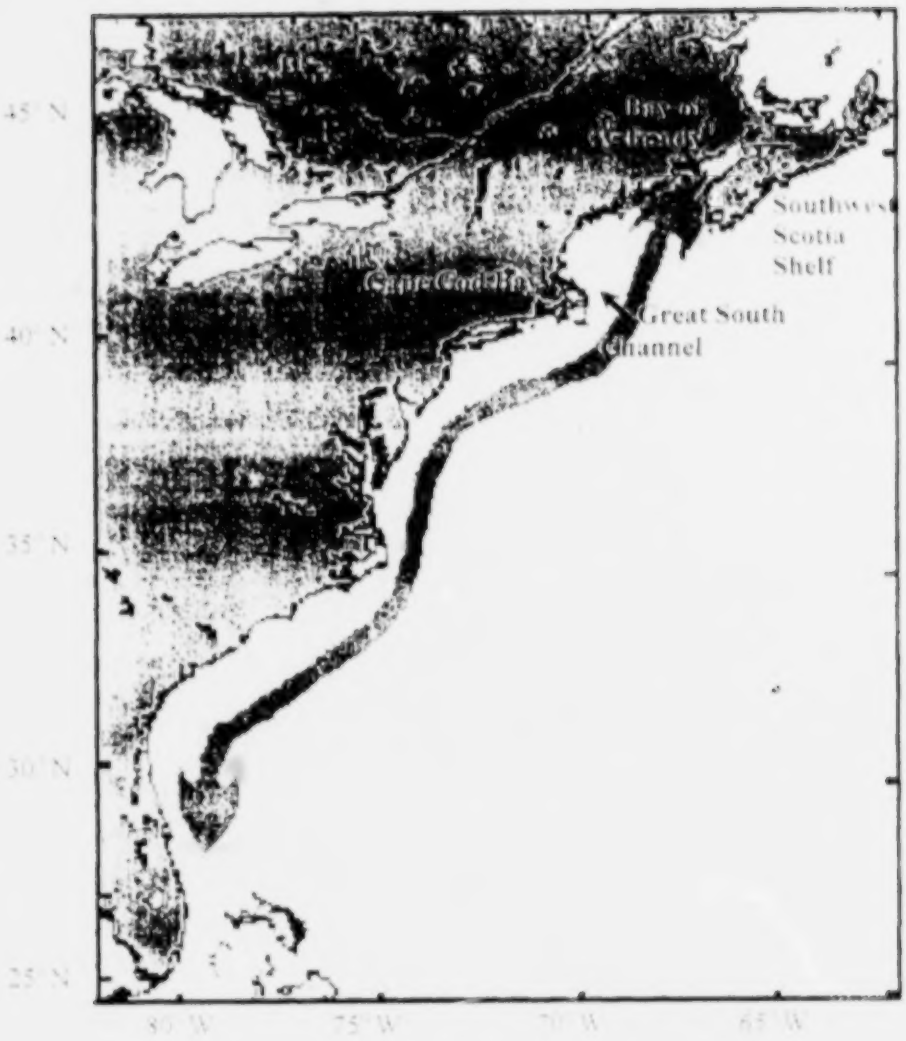

Figure 1.1.1: The migration route and critical habitat of the North Atlantic right whale

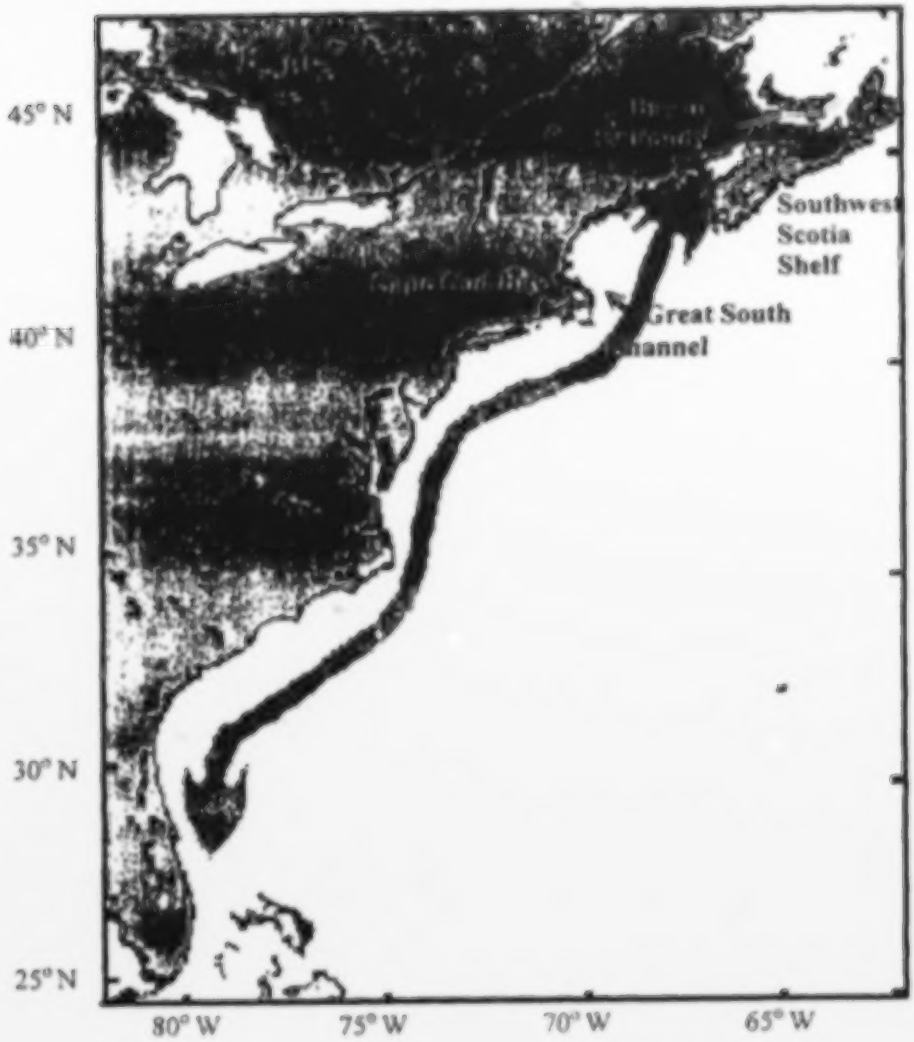

Figure 1.1.1: The migration route and critical habitat of the North Atlantic right whale.

The population scatters in the winter months with some animals observed in the coastal waters of Florida and Georgia. Little is known about the winter distribution of the remainder of the population that is thought to consist of mainly males and non-pregnant females (Schaeff *et al*, 1992). Large aggregations of right whales are found in April in Cape Cod Bay and the population then disperses north to the south-west Scotian Shelf and Bay of Fundy where the majority can be found from July through October (Gaskin, 1991). Concentrations of right whales have been identified in the Cape Cod Bay, Great South Channel, south-western Scotian Shelf, and Bay of Fundy (Figure 1.1.1) and these locations are considered critical habitats (Winn *et al*., 1986).

The contemporary distribution of right whales appears more contracted relative to the historical distribution. Historically (pre-whaling ≈1500s), in eastern Canada, right whales were found in abundance in the Gulf of St. Lawrence and along the southern shores of Newfoundland (Hay, 1985). That distribution has contracted. For example, aggregations of North Atlantic right whales usually encountered in the Roseway Basin region of the Scotian Shelf have not been detected by recent surveys (Clapham and Cole, 1999). The contemporary geographic limits of the distribution of the North Atlantic right whale are unclear. For example, "Porter" an adult male was observed in the Norwegian fjord Kvaenangen in September, 1999. His last sighting before then was four months earlier in the north-eastern part of the Great South Channel (Marx *et al*. 1999). North Atlantic right whales may range among a number of areas without establishing residence in the known critical habitats (Mate *et al*., 1997).

1.3 The Bay of Fundy

The Bay of Fundy is a seasonal critical habitat for North Atlantic right whales and represents the only known summer nursery, where two-thirds of the reproductive females take their calves (Schaeff *et al* , 1992). The Bay of Fundy also represents one of two known feeding areas for the July through October season (Winn *et al*., 1986). Large aggregations of right whales (~ 200 animals) have been estimated in the Bay of Fundy habitat at one time (Philip Hamilton, New England Aquarium, Boston, Massachusetts, pers comm). In 1994, the Grand Manan Basin area was designated as a conservation area

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by the Canada Department of Fisheries and Oceans (Anon., 1999). Unfortunately, this same area intersects a ship traffic separation scheme approved by the International Maritime Organisation. The major outbound shipping lane from St. John, NB passes directly through the conservation area. This poses a ship collision threat to the majority of the remaining right whale population as they feed and nurse for four months of the year.

1.4 Human-Whale Interactions

Shipping lanes into Boston, New York, and Portland also intersect the migratory routes of right whales. Right whales move through these shipping lanes (Mate *et al.*, 1997), but in contrast to the Bay of Fundy, the animals do not take up residency in those areas. As right whales spend extended periods in the Bay of Fundy, in close proximity to shipping lanes, the probability of collisions is elevated. Ship strikes accounted for 36% (16/44) of the documented mortality of North Atlantic right whales between 1970 and 1999 (Anon, 1999) Of these mortalities, 56% (9/16) occurred within the last ten years and 4 occurred in Canadian waters (Anon, 1999). The low frequency of propeller wounds observed in the living population, relative to the known mortalities caused by ship collisions, indicates that ship collisions are deadly (Kraus, 1990). In 1986, a ship strike killed a right whale near Provincetown, Massachusetts. The propeller of the ship inflicted longitudinal lesions measuring 1 m deep and 5 m in length and the ultimate cause of death was a shattered spine (Kraus, 1990). In other cases, the size of wounds in both the scarred living and dead animals can most likely be attributed to the propellers of container ships, tankers, and military vessels (Kraus, 1990). Minor vessel collisions may not kill the animal directly, but they may weaken the animal as lethal infections can develop in wounds. Interactions with human activities are a significant source of mortality in the North Atlantic right whale (Kraus, 1990; Kenney and Kraus, 1993).

Fishing activity also threatens the survival of the North Atlantic right whale, as the whales frequently become entangled in fishing gear. Entanglements are considered more frequent than ship collisions but appear to be less lethal to the whales. The type of gear includes gill nets, weirs, cod traps, long lines, and lobster traps. The gear and moorings can be caught in the mouth, or wrapped around the body or tail of an animal

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(Kraus, 1990). A subset of the catalogued right whales (17%, 28/161) exhibit scars characteristic of gear entanglement around the mouth, while 57% (67/118) have visible scars in the peduncle region (Kraus, 1990). Since 1970 there have been 31 records of entanglement, three of which were directly fatal and 11 others are thought to have eventually proved lethal. (Right Whale News, as cited in Knowlton and Kraus, in press). Observations among stranded whales (1970 to 1989) indicate that one third of the right whale mortalities resulted either from entanglements or ship collisions (Kraus, 1990).

1.5 Early Warning Systems

If the prospects of the North Atlantic right whale population are to improve, human induced mortality must decrease (Caswell *et al.*, 1999), and efforts to decrease threats to North Atlantic right whales will assist recovery of the population (Kenney *et al.*, 1994). Recently, an increased importance has been placed on developing recovery plans for this species. Canada has designated three areas on the east coast as East Coast Whale Sanctuaries and developed a Caution to Mariners, describing the history and background of the North Atlantic right whale and giving the location of the sanctuaries (Conway, 1997). One potential solution to the problem of ship strikes is an early warning system of right whale presence to vessels travelling through critical right whale habitat. Systematic surveys over a particular area, using boats, airplanes or helicopters can provide information on the location and movement of right whales to a central traffic control station to warn other vessels travelling through the area. The New England Aquarium has been conducting such surveys in the southeastern United States since 1984 (Slay, 1997). Other areas in the US are beginning to follow suit and the Northwest US Early Warning System Survey started surveying using a helicopter as well as two marine vessels for surface surveillance off the coast of Massachusetts in 1997. These surveys are important for locating whales in heavy traffic areas not only to warn vessels travelling through the area but also for spotting whales entangled in fishing gear.

In the Bay of Fundy there were 67,000 vessel movements in 1995/1996, exclusive of fishing and recreational vessels (Miller, 1997). Any vessels entering these areas are required to report to Fundy Traffic Control. Actions to reduce the probability of ship

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strikes in Canadian waters have included speed reduction when whales are sighted and if possible, course changes However, with these procedures, since 1992, three documented mortalities (27% of all known ship strikes; Brown *et al*, 1999) have resulted from ship strikes in the Bay of Fundy

Another possible solution to ship strikes, and potentially useful to decrease the death attributed to fishing gear entanglements, is an early warning system based on an underwater hydrophone array moored in local habitat such as the Grand Manan Basin area where there is extended residency. An acoustical array would allow localisation of whale vocalisations and could be used for real-time tracking of whale movement. The benefits of an acoustic array relative to the conventional visual methods of surveying include the low cost of operation and the ability to monitor over all hours of the day Furthermore, an acoustical array would not be limited by local weather conditions, search patterns, the frequency of searches, nor observer bias, which are all factors that hinder the contemporary survey-based detection methods (Hain, 1997). The passive acoustic surveillance approach would provide relatively high-resolution scientific information on the distribution of the population in time and space, as well reduce the probability of ship collisions It would also provide statistics on time-varying distribution and migration patterns, needed for reducing fishing gear conflicts in a local area.

1.6 Acoustic Arrays

Using acoustical arrays for listening to the oceans is not new. The world's navies have been listening to the oceans since the Second World War and the US Navy is now using similar technology to monitor baleen whale movements using an Integrated Undersea Surveillance System (IUSS; Nishimura and Conlon, 1994). IUSS can be used for the detection of low frequency sounds (<200Hz) that include finback (*Balaenoptera physalus*) vocalisations, the lower range of humpback (*Megaptera novaeangliae*) songs, minke (*Balaenoptera acutorostrata*) and blue whale (*Balaenoptera musculus*) vocalisations. However this range does not include all right whale vocalisations. Ljungbland *et al* (1981) used sonobuoy recordings as possible indices for detecting the presence of migrating bowhead whales (*Balaena mysticetus*). Underwater vocalisations

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have also been used to determine the migration routes of gray whales (*Eschrichtius glaucus*, Crane and Lashkari, 1996). Hazen and Desharnais (1997) determined the regional seasonality of finbacks on the Scotian Shelf and Grand Banks by relying on the strong vocalisations at 20 Hz. Clark (1980) designed and built a real-time device to determine the direction of the underwater sounds of the Southern right whale. His main objective was to associate the vocalisations with the behaviour in non-captive populations of whales.

Acoustical monitoring with such an array requires *a priori* knowledge of the sounds being monitored Previous studies have characterised the vocalisations of the Southern right whale (Clark, 1983; Clark, 1982; Payne and Payne, 1971) and North Atlantic right whales have been noted as similar to the southern (Thompson *et al.*, 1979, Richardson *et al.*, 1995). However, few acoustic data have been collected for the North Atlantic right whale and even fewer have been analysed. Of the recordings for the North Atlantic right whale, Schevill (1962) published one sonogram from recordings made in the waters off Martha's Vineyard. Cummings and Phillipi (1970, as cited in Winn and Olla, 1979) reported repetitive patterns of vocalisations or "stanzas" off the coast of Newfoundland that were later refuted by Payne and Payne (1971) who attributed these vocalisations to humpback whales Spero (1981) studied the vocalisation patterns and corresponding social interactions of North Atlantic right whales in the Bay of Fundy, however the work published from this study was an abstract and provides no quantitative information that can be used for comparisons. Many questions remain unanswered about the vocalisations of the North Atlantic right whale that would allow for the acoustical monitoring of this species

A pilot study was conducted in the summer of 1999 and was designed to record and compile data on the vocalisations of the North Atlantic right whale in the Bay of Fundy and to assess the viability of employing an acoustic array as a monitoring system for right whale presence

The objectives of this study are to characterise the underwater vocalisations of the North Atlantic right whale by examining and quantifying fundamental frequencies, durations, modulations, harmonics, and time between vocalisations and to compare these

characteristics with those determined by other data derived from Northern and Southern right whales

2. METHODS

2.1 Recording

Sound recordings were made in the Grand Manan Basin, Bay of Fundy, Canada (Figure 2.1.1), over a 4-hour period in the morning and early afternoon (AST) of 29 July 1999. Recordings were made in calm conditions with moderate to heavy fog from a drifting 29-foot research vessel, the RV *Neirid*. A Cetacean Research Technology hydrophone (bandwidth 12 Hz to 35 kHz) and a Sony Portable MZ-R50 minidisk recorder with a sampling frequency of 44.1 kHz were used for data collection. Recordings were made at 8 locations (Figure 2.1.1) by creating a new track on the minidisk for each location in the Grand Manan Basin. Approximately two hours of data were recorded. The locations of individual right whales were noted when observed (Figure 2.1.1), as well as the start positions of each recording. All locations were obtained using a GPS system. The hydrophone was deployed between 6 and 10 meters below the surface from the port side amidship Once the whales appeared to have departed from the immediate area, the vessel would move to a new location where right whales were known to be present (heard or seen).

Simultaneously recordings were made from an array of 16 sonobuoys variously capable of receiving frequencies up to 2 kHz and 10 kHz (Figure 2.1.1). Sonobuoys were radio linked to the 415 Maritime Patrol "Swordfish" Squadron out of CFB Greenwood, NS (monitored by Francine Desharnais, DREA). Approximately 3 hours of concurrent recordings were obtained.

2.2 Analysis

The time-on-track and the track number of individual vocalisations were noted by listening to the minidisk recordings. The audio analogue output from the minidisks was acquired on a PC-NT computer using a SoundBlaster ® card providing a record for each channel. Recordings were electronically filtered using a 100 Hz to 2 kHz band pass filter (i.e. retaining frequencies between 100 and 2000 Hz with a roll-off of 40 dB per decade at the start and end of the band pass). Preliminary data exploration suggested the vocalisations would not be effected by this band pass that reduced the < 100 Hz noise.

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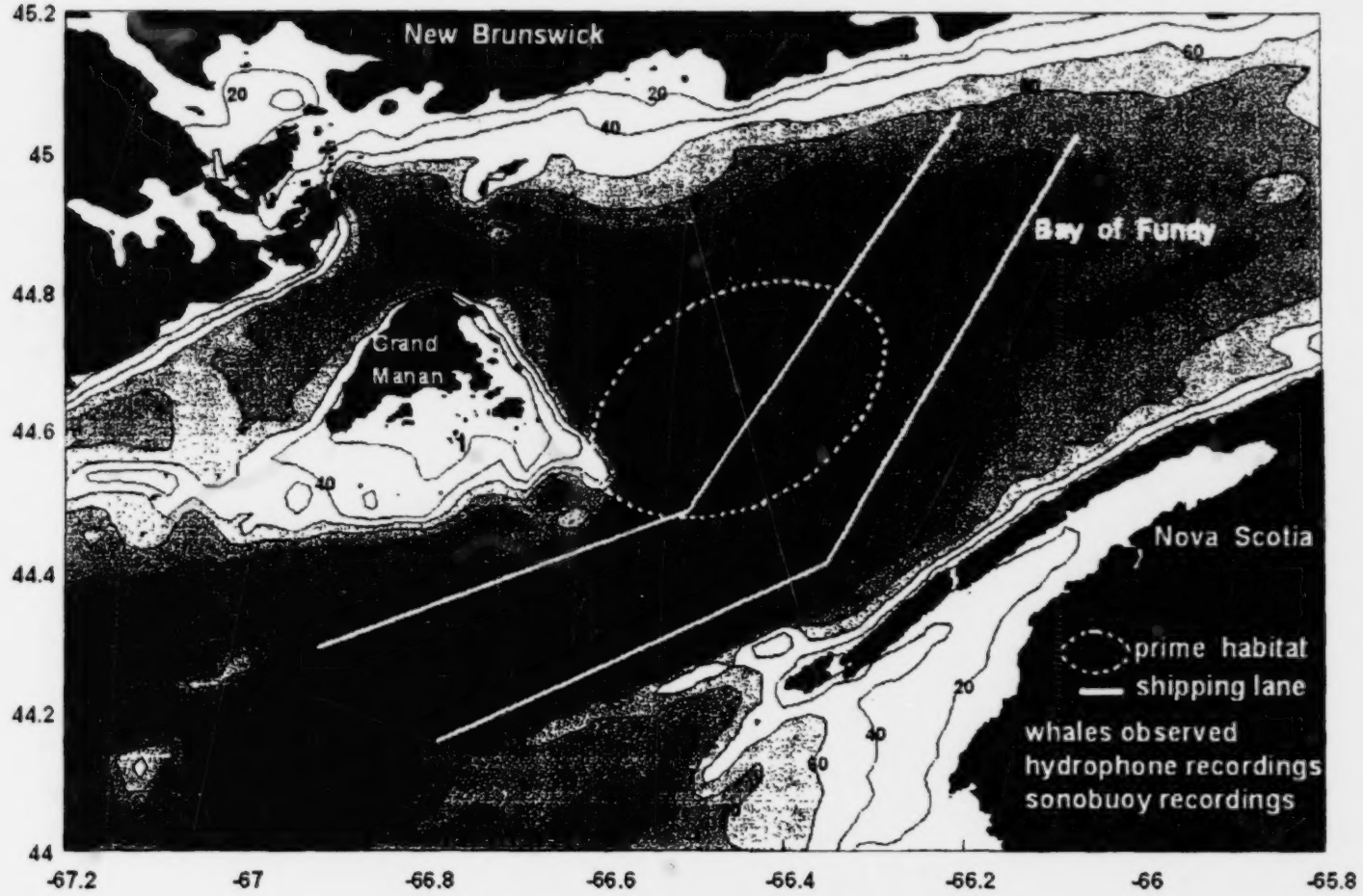

Figure 2.1.1: Bathymetric chart of the recording locations and the intersection of prime right whale habitat by the shipping lanes in the Bay of Fundy. Bathymetric contours are at 20 m intervals.

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The recordings were digitised using Goldwave (Ver. 4.1) at a sampling frequency of 5000 Hz and 16 bit resolution. Two channels were digitised: the analogue output signal from the minidisk; and a separate channel for logging a manual event marker (voltage pulse) used to mark the locations of the aurally detected vocalisations within the recordings. Digitisation was done by tracks and then the track files were separated into smaller files containing each audible individual vocalisation.

2.3 Measurement

All measurements were computed using custom programs operating within MATLAB (Ver. 5.3, The Mathworks, Inc 1998). Power spectral density (psd) estimates were calculated with a frequency resolution of 5 Hz, using the MATLAB routine psd. This function provided the parameters used in the spectral analysis of the vocalisations. Once the spectrogram was calculated, each vocalisation was replayed and an approximate peak frequency ($f_\bullet$) was estimated from the spectrogram. The signal was then bandpass filtered digitally within a frequency band at 0.75 $f_\bullet$ to 1.8 $f_\bullet$. The filtered signal was played once again to ensure the vocalisation was within the filtered band.

To isolate individual vocalisations a "section" or box of the spectrogram was defined using the ginput function in MATLAB. The section of the spectrogram extracted, began immediately prior to the visual start of the vocalisation, and terminated after the visual end of the vocalisation, and a buffer of approximately 0.1 seconds was used on either end of the vocalisation (Figure 2.3.1). Within each section, the frequency of maximum intensity (f_m) was determined through time (t). The peak frequency of the vocalisation as a function of time, $f_p(t)$, was determined from the intensity-weighted mean of the spectral densities within a 25 Hz window centred on $f_m(t)$.

Each spectrogram section was also used to determine the noise floor (the intensity of the ambient noise in the recordings). Once the peak frequencies were calculated for each section the spectral densities were integrated over the frequency within the section, to provide the total intensity levels as function of time. The vocalisation (signal) intensity levels were computed by integrating the spectral densities over 5 frequency bins centred at $f_m(t)$ (representing a range of 25 Hz around the peak frequency). This

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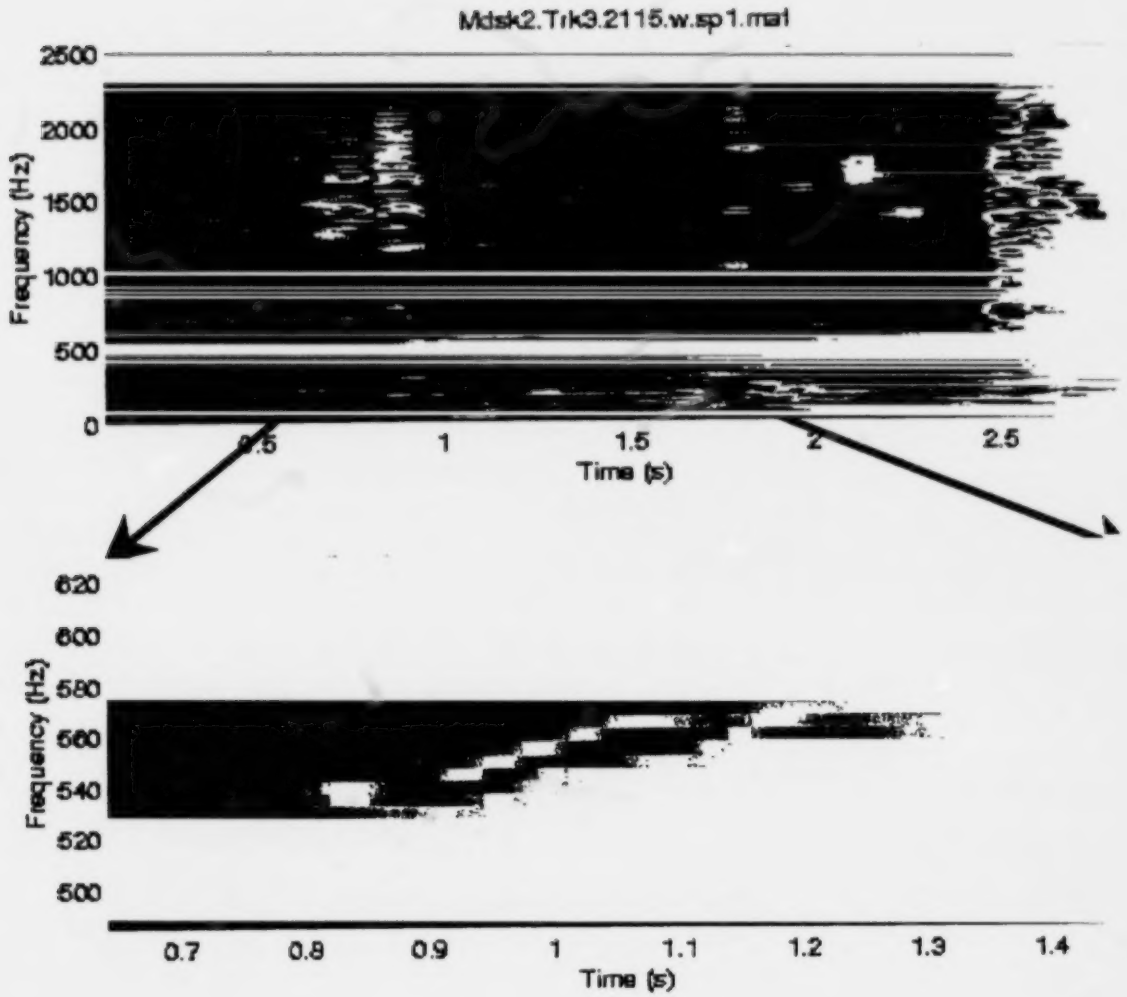

Figure 2.3.1: Isolation of individuals vocalisations: a section or box was defined using the ginput function in MATLAB. This section (below) was extracted from the entire spectrogram (above) and the peak frequency through time within the box was calculated.

integration gave the intensity level (signal variance) of each vocalisation through time, at 6.4 ms intervals. The difference between the total intensity and the signal intensity provided the noise floor or the intensity of the ambient noise in the section. The start of a vocalisation was defined as the time when the signal's intensity rose above the noise floor and the vocalisation would end at the time when the signal fell below the noise floor (Figure 2.3.2).

2.4 Time Frequency Domain Features

Vocalisations were examined for the presence of harmonics by visually examining the spectrograms as well as examining frequency versus spectral density for each entire vocalisation and then again by using smaller time sections of a vocalisation (necessary to "see" through the noise). Using the mean fundamental frequency from each vocalisation, the change in frequency relative to the mean peak fundamental frequency through time (every 6.4 ms) was also calculated to provide a measure of relative frequency modulation.

2.5 Time Domain Features

The time-on-track (t_i) for all tracks was calculated to the nearest second using the original minidisk recordings. Clustering analyses were performed first by including the time to the first vocalisation, and subsequently by using only the difference between the time-on-track and the time to the first vocalisation (t_i-t_1). To simulate a Poisson process, 20 sets of time-on-track data were generated using an exponential distribution with a rate of 1 vocalisation per minute with a sample size of 20.

2.6 Statistical Analysis

The measured variables: peak fundamental frequency, amplitude-weighted mean frequency, mean fundamental frequency, duration and modulation of each vocalisation, and the time between vocalisations were imported to the statistical package NCSS (Ver. 97, Hintze, 1998) for basic descriptive statistics and distribution analysis. Kruskal-Wallis

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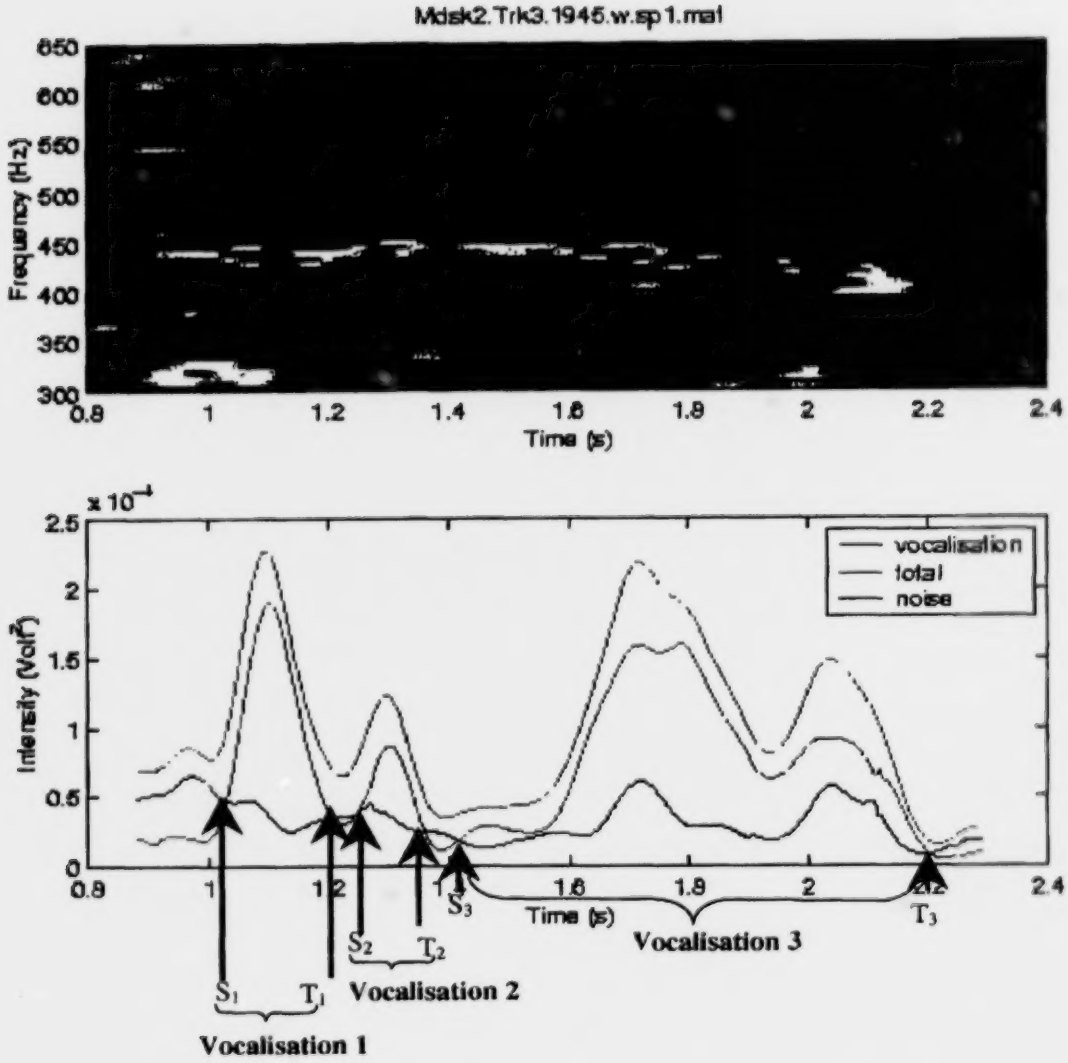

Figure 2.3.2: Spectrogram (above) and the corresponding spectrum (below) of right whale vocalisations. A vocalisation was defined as the interval where the vocalisation intensity exceeds the noise intensity. Thus, in this example the vocalisation is divided into three separate vocalisations. S denotes the start of vocalisation and T indicated the end or termination of the vocalisation.

tests were used to test for differences between the medians of the means and amplitude-weighted means of the fundamental frequency for each vocalisation. The time-on-track (t_i) medians for sequential vocalisations using the observed data as well as the simulated data (see below) were tested for differences using Kruskal-Wallis tests.

Using varying window widths, the number of events or vocalisations were recorded and tested against a Poisson distributions using a maximum likelihood function (MLE) for goodness of fit. The Greenwood statistic (Stephens, 1986) was used to determine if the intervals between events were exponentially distributed (i.e. event times constitutes a Poisson process) It also specifically tests for uniformity in the time between vocalisations.

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3. RESULTS

Fifty-three vocalisations, presumed to be North Atlantic right whales (see discussion section 4.5), were identified within a total of two hours of recordings. Of these 53 vocalisations, the data from 45 were of sufficient quality and were used in the analyses of their basic characteristics; mean fundamental frequency, duration, relative frequency modulation, overall change in frequency, the overall change in frequency relative to mean fundamental, and the presence of harmonics and non-harmonic frequency bands (Table 2.1). The cluster number and sequences within clusters of vocalisations are also summarised in Table 2.1. The North Atlantic right whale has an extensive repertoire and only a small portion is assessed here. Simple vocalisations, low frequency moans and trumpets are qualitative descriptors of the kinds of vocalisations captured in the recordings.

3.1 The Fundamental Frequency

The mean and the amplitude weighted mean for each fundamental frequency (the peak frequencies through time (*fp(t)*), were not significantly different (Kruskal-Wallis test, p-value = 0.91), and thus all further calculations used the mean fundamental frequency. The mean peak frequency or the mean fundamental frequency was calculated for each vocalisation and ranged from 65 Hz to 1535 Hz (Figure 3.1.1, Table 2.1).

The majority, 82 % (37/45), of the mean fundamental frequencies ranged from 340 to 600 Hz with a median of 484 Hz (Figure 3.1.1, Figure 3.1.2).

Two vocalisations were detected (auditory) at very low frequencies. The first of these low vocalisations was separated into three parts and analysed as three separate vocalisations because of the high noise levels at lower frequencies. The second vocalisation (Figure 3.1.3) was also separated into two parts due to the greater intensity of the noise floor. This lower range of vocalisation (fundamental < 200 Hz) accounted for 11% (5/45) of the analysed vocalisations.

The remaining vocalisations (n = 3) occurred at higher frequencies with no discernible real grouping or pattern and had a large range of mean fundamental

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Table 3.1. Summary of all vocalisation that were included in the analysis. Characteristics include mean fundamental frequency (Hz), duration (s), overall modulation relative to the mean fundamental frequency, as well as the sequence in a cluster and the corresponding cluster number.

Vocalisation	Cluster #	Sequence in Cluster	Mean Fundamental Frequency (Hz)	SD (Hz)	Duration (s)	Initial Frequency (Hz)	Final Frequency (Hz)	Overall Change In Frequency (Hz)	Overall Change in Frequency relative to mean Fundamental	Harmonics & Non-harmonic Frequency Bands
mlt7-0405			477 57	6.80	0 57	489.89	472.18	-17 71	-0.04	
mlt7-1458	1	3	406 28	1.10	0 81	406.55	404 67	-1 87	0.00	2nd, 3rd, and 4th harmonic
mlt7-2721a	2	1	458 16	0.40	0 08	458.67	457.18	-1.49	0.00	
mlt7-2721b	2	1	454 07	10.10	0.27	450.71	469.58	18.86	0.04	
mlt7-2727	2	2	486 51	13.30	0.37	500.87	490.69	-10.18	-0.02	Non-harmonic band ~2000 Hz
mlt7-2853	3	1	484 41	20.60	0 44	527.86	477 75	-50 11	-0.10	Non-harmonic bands ~1400 Hz and ~1900 Hz
mlt7-2901	3	2	592 66	5.30	0 53	591.29	605 26	13 97	0.02	
mlt7-2904	3	3	514 32	4.10	0 61	523.39	514 94	-8.44	-0.02	Non-harmonic band ~2100 Hz
mlt72953			486 76	3.10	0.27	484.16	494 41	10.26	0.02	
mlt7-3458			935 58	2 60	0 09	934.34	943 68	9.34	0.01	
mlt8-0101			472 54	28.40	0.32	480.42	523.56	43.14	0.09	
mlt9-0311	4	1	491 16	12.10	0 47	455 15	499.99	44.84	0.09	
mlt9-0321	4	2	483 92	6.00	0.35	481.67	483 35	1.68	0.00	
mlt9-0326a	4	3	538.21	1.50	0.11	535.57	538 34	2 77	0.01	
mlt9-0326b	4	3	507 78	1.90	0 16	531.18	510 42	-20.76	-0 04	
mlt9-0426			487 67	1.10	0 27	491.64	487 48	-4.16	-0.01	2nd harmonic

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Table 3.1 Continued:

Vocalisation	Cluster #	Sequence in Cluster	Mean Fundamental Frequency (Hz)	SD (Hz)	Duration (s)	Initial Frequency (Hz)	Final Frequency (Hz)	Overall Change In Frequency (Hz)	Overall Change in Frequency relative to mean Fundamental	Harmonics & Non-harmonic Frequency Bands
m1t9-0711	5	2	488 32	3.40	0 10	493 50	483.09	-10.41	-0 02	
m2t2-0755			459 47	17 50	0 39	431 98	466.98	35.00	0.08	
m2t2-0854			355 86	7.30	0 27	372.51	350.39	-22.12	-0.06	
m2t2-0931			436 59	5 60	0 37	446 94	450.78	3 84	0.01	
m2t2-1249			456 01	1.00	0 18	459 99	455 75	-4 24	-0 01	
m2t2-1505a			136 41	4.50	1.26	138 70	137 16	-1.54	-0.01	
m2t2-1505b			134.54	1.00	0.37	135 94	136.27	0 33	0 00	
m2t2-1505c			133 70	2 40	0 68	134.21	126.60	-7 61	-0.06	
m2t2-1654			569 09	9.00	0 22	559 96	574.20	14 24	0.03	2nd harmonic
m2t2-1755a			69 76	4.60	0.27	71.82	70.44	-1.38	-0.02	2nd harmonic
m2t2-1755b			67 26	0.48	0.25	67.65	67 42	-0.24	0.00	2nd harmonic
m2t2-2348			1536 34	4.30	0.26	1540 06	1528.04	-12.01	-0.01	
m2t3-1653			405 71	4.70	0 24	409.73	422.78	13.05	0.03	
m2t3-1903	7	1	428.77	2.80	0 80	438.06	431.68	-6 38	-0.01	
m2t3-1905	7	2	532 39	16.60	0 33	560 38	510 97	-49.41	-0.09	
m2t3-1933	8	1	344.10	6.40	0.21	338.43	353.64	15.21	0.04	
m2t3-1936	8	2	518.54	8 90	0 48	503 66	565.14	61.48	0 12	
m2t3-1939a	8	3	525 98	7.20	0 50	568.36	530 12	-38.24	-0 07	2nd, 3rd, and 4th harmonic
m2t3-1939b	8	3	578.05	13.80	0 51	600 87	553.30	-47 57	-0.08	2nd, 3rd, and 4th harmonic
m2t3-1945	8	4	433.38	11 00	1 18	439 80	404.90	-34.90	-0 08	Non-harmonic band ~1750 Hz

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Table 3.1 Continued·

Vocalisation	Cluster #	Sequence in Cluster	Mean Fundamental Frequency (Hz)	SD (Hz)	Duration (s)	Initial Frequency (Hz)	Final Frequency (Hz)	Overall Change In Frequency (Hz)	Overall Change in Frequency relative to mean Fundamental	Harmonics & Non-harmonic Frequency Bands
m2t3-1948	8	5	1357.46	2.20	0 60	1360 72	1360.40	-0.32	0.00	
m2t3-2011	9	1	346 89	9 60	0.29	268 17	344.63	76.46	0.22	
m2t3-2019	9	2	361 41	13 60	0 46	391 20	359 13	-32.07	-0 09	
m2t3-2108	10	1	525.25	2 30	0.36	511.59	521 91	10.31	0 02	
m2t3-2115	10	3	553.38	11.50	0 57	541.26	569 70	28.44	0 05	
m2t3-2119	10	4	562.71	2 50	0 16	562 72	570.15	7.43	0 01	
m2t3-2123	10	5	484 42	10.10	0.75	460.37	478 56	18.19	0.04	2nd, 3rd, and 4th harmonic
m2t3-2148	11	1	379.28	6 20	0.60	397.51	382.03	-15.48	-0.04	
m2t3-2154	11	2	409 10	6 00	0.36	406.98	423.30	16.32	0 04	

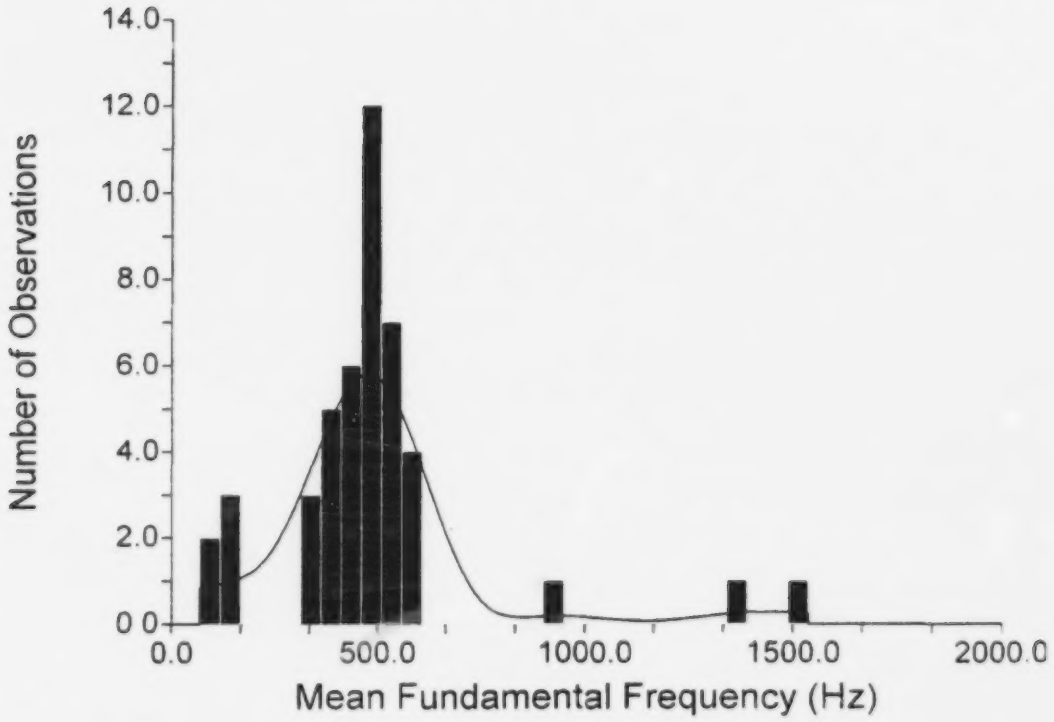

Figure 3.1.1 The distribution of the mean fundamental frequency (Hz). The majority of the vocalisations occur between 340 to 600 Hz.

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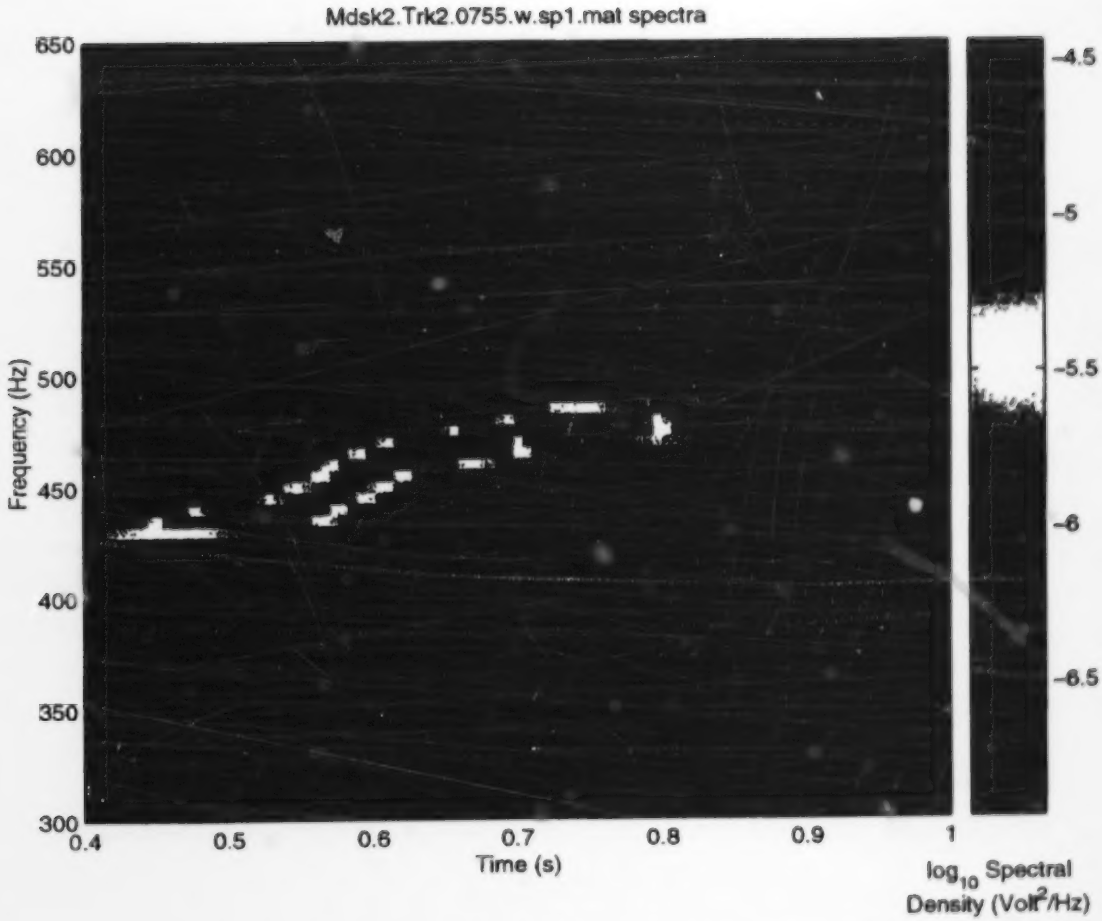

Figure 3.1.2: Spectrogram of an upsweeping right whale vocalisation with a mean fundamental frequency of 459 Hz.. Also note the broadband features immediately before and after the vocalisations: this is "noise".

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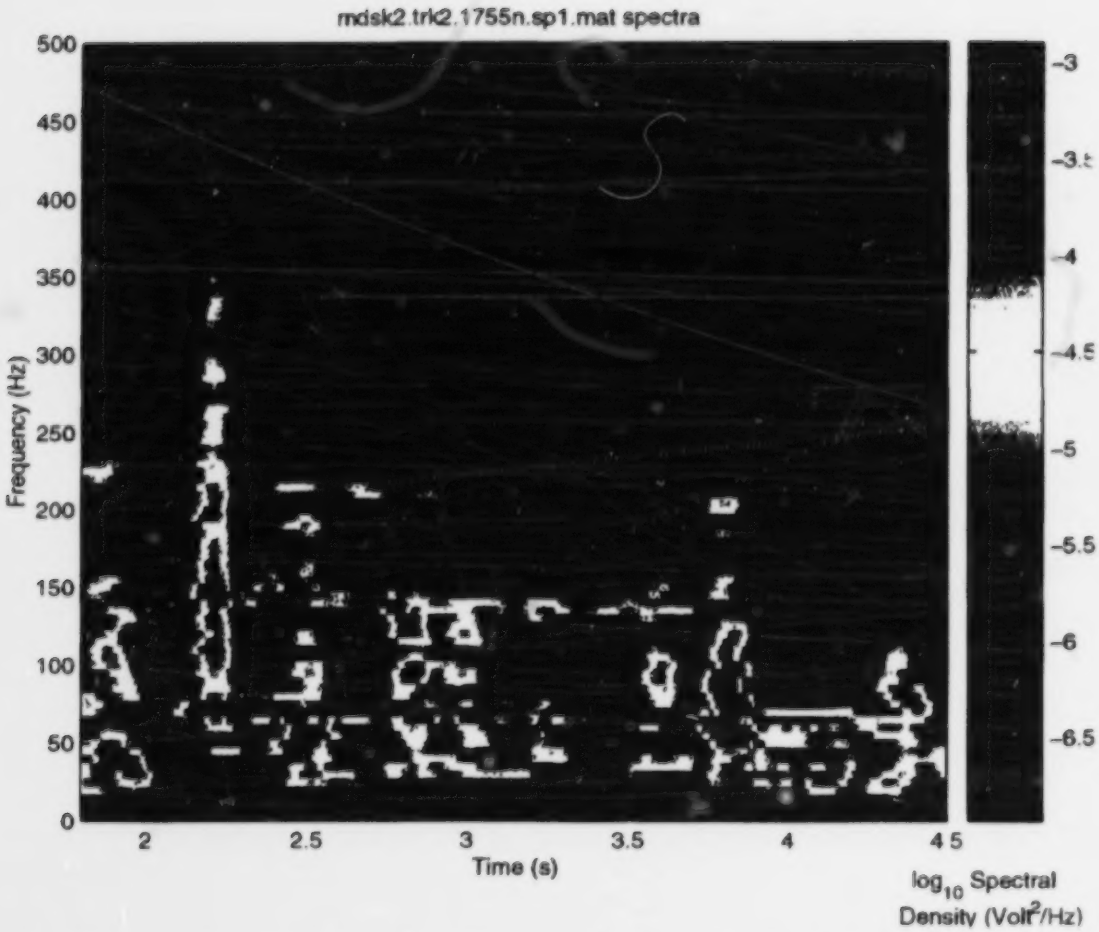

Figure 3.1.3: Spectrogram right whale vocalisation with a mean fundamental frequency of 68 Hz and the first harmonic at ≈ 140 Hz. There is also frequent occurrence of broadband "noise" typically lasting 0.15 seconds; e.g. at 2.25 s.

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frequencies. The three vocalisations have mean fundamental frequencies of 935.6 Hz, 1357 5 Hz and 1536.3 Hz (Figure 3.1.4). There were two other vocalisations at these higher frequencies, but their intensity was too low for analysis. Using high pass and low pass filters, the vocalisation was filtered and replayed, and then filtered again in increments of 100 Hz, until the vocalisation could no longer be detected aurally. The fundamental frequency of the first vocalisation was estimated at 1600 Hz, the second was estimated at 1900 Hz

3.2 Frequency Modulation

Several vocalisations changed through time and were frequency modulated. Upsweeps (Figure 3.1 2), down-sweeps (Figure 3.2.1) or a combination (Figure 3.2.2) of both are observed in almost all vocalisations. The frequency modulation from the start of a vocalisation to the end varied from 0 Hz to 76 Hz. The greatest frequency modulation relative to the mean fundamental frequency is represented by ± 20% for all vocalisations (Figure 3.2.3). Relative modulation greater than 10% around the fundamental frequency was rare. The cumulative percentage at each level of relative modulation allows the calculation of a 95% confidence interval for modulation relative to the mean fundamental frequency, which is [–0.082 0.046].

3 3 Multifrequency Vocalisations

Harmonics, frequency bands or tones at integer multiples of the fundamental frequency (Figure 3.3.1) and non-harmonic frequency bands above the fundamental frequency (Figure 3 3.2) were observed in 27% of the vocalisations. The second harmonic (2* fundamental frequency) was observed in 9% (4/45) of the vocalisations and another 9% (4/45) contained second, third and fourth harmonics. Non-harmonic frequency bands were less common than harmonics and were observed in 9% (4/45) of the vocalisations.

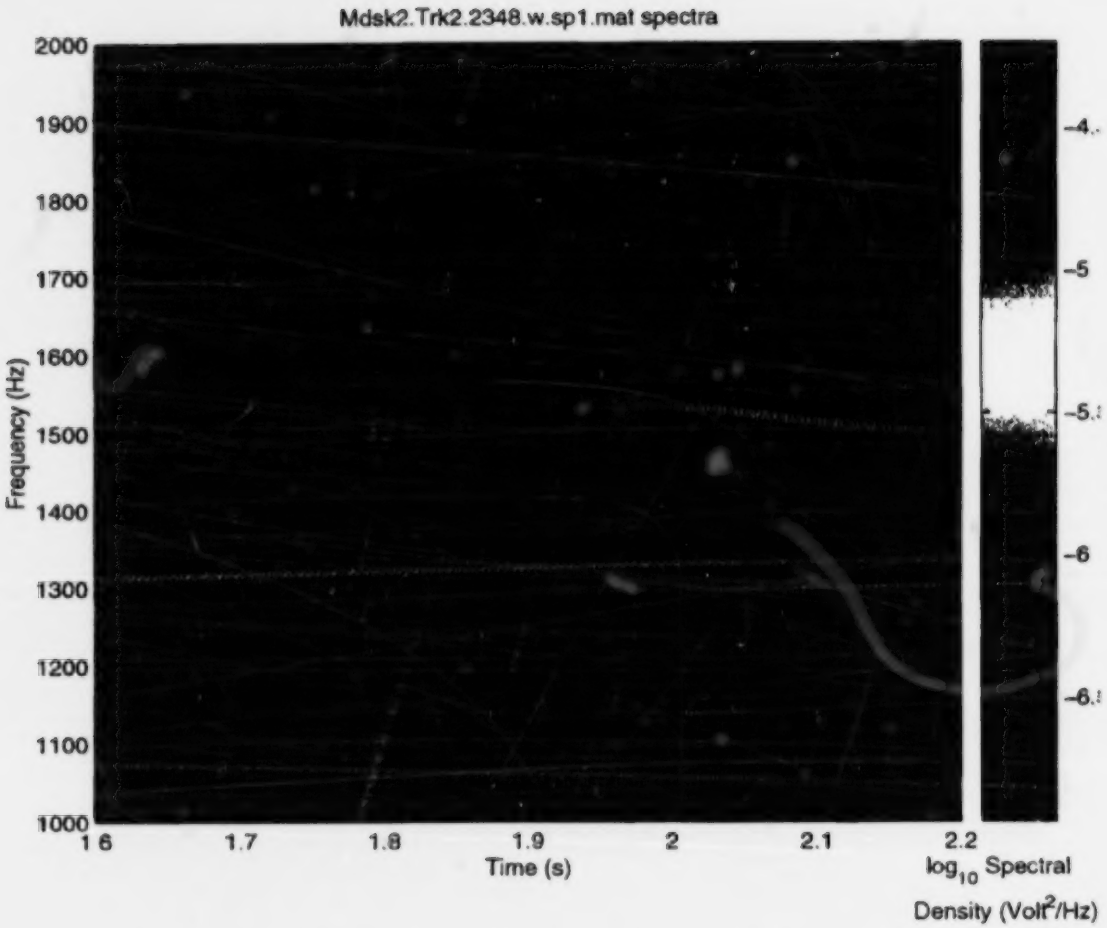

Figure 3.1.4:Spectrogram of right whale vocalisation with a mean fundamental frequency of 1536 Hz. The intensity of the vocalisation is greatly reduced compared to majority of vocalisations that are found in the frequency band of 340 to 600 Hz.

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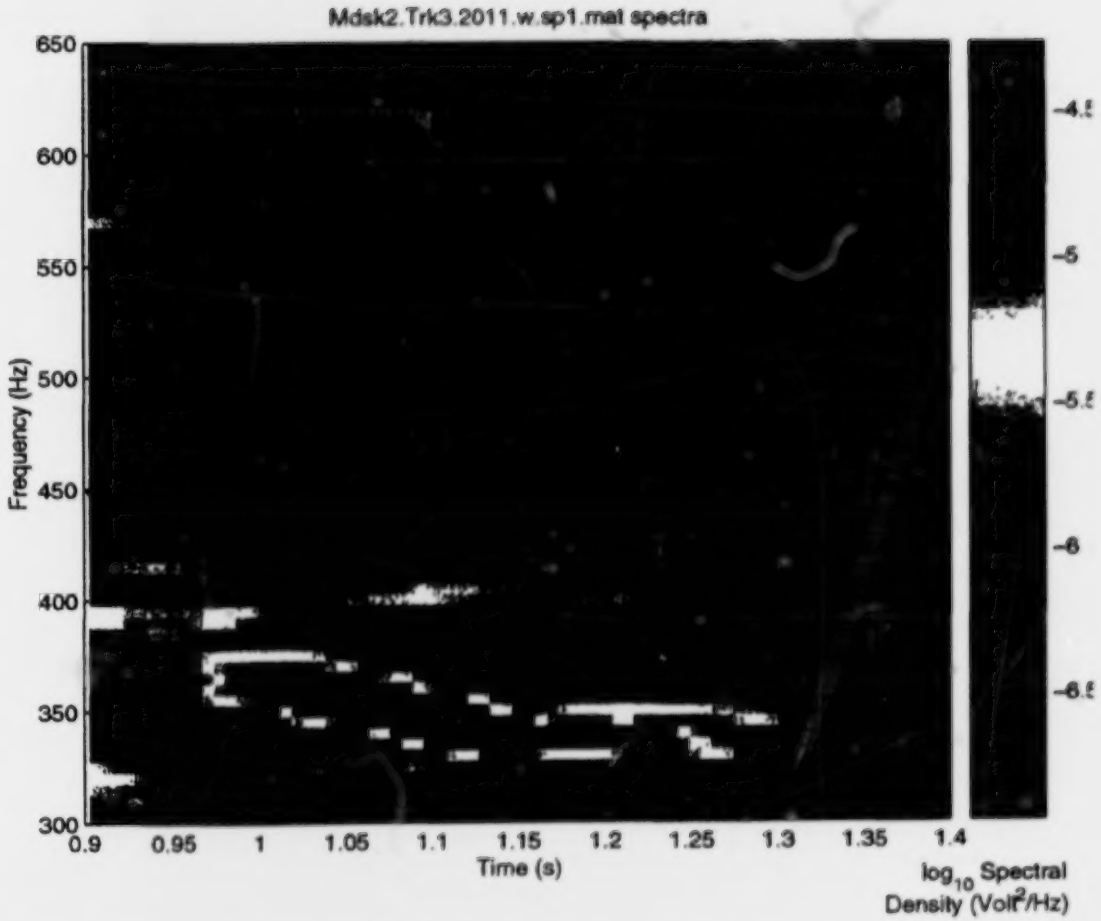

Figure 3.2.1: Spectrogram of a down-sweeping vocalisation with a mean fundamental frequency of 347 Hz.

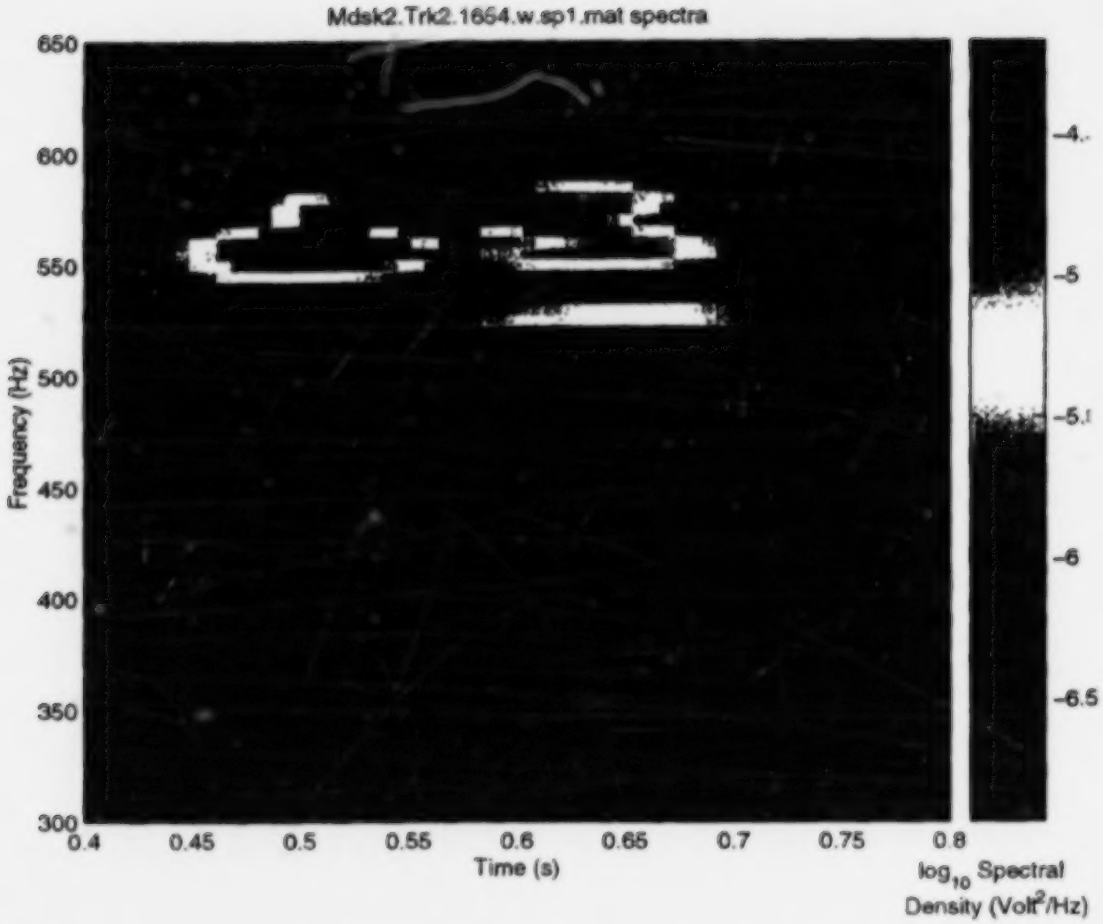

Figure 3.2.2: Spectrogram of a vocalisation containing an upsweep as well as a small downsweep. The vocalisation frequency starts at 559 Hz, swings up, levels off at 575 Hz and then sweeps down back to the initial frequency.

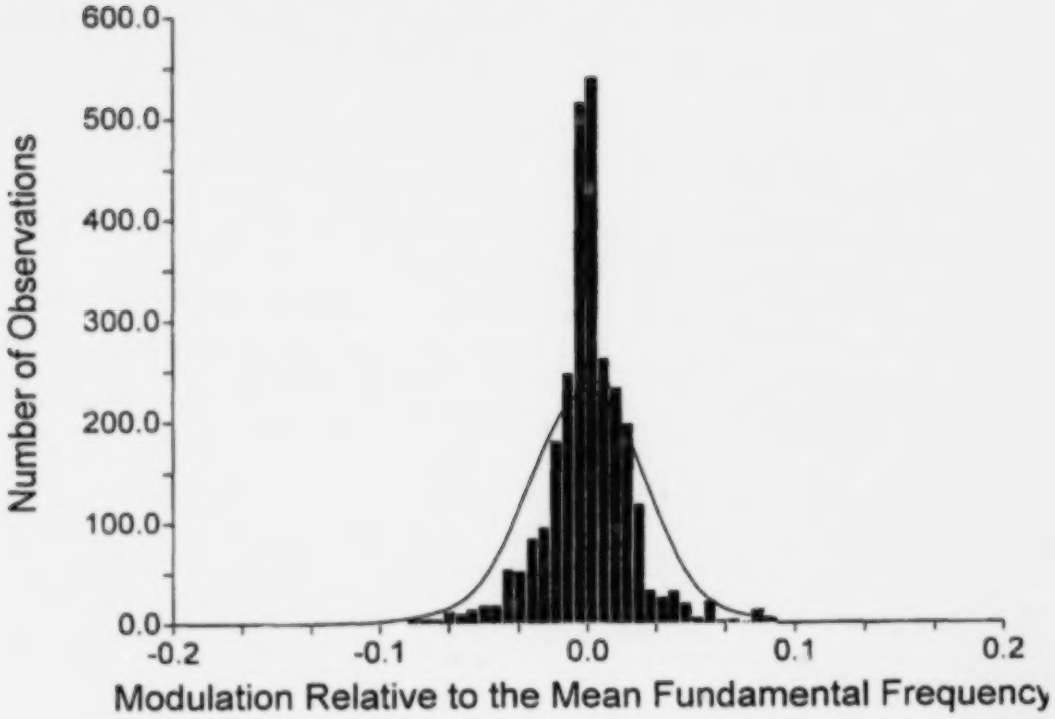

Figure 3.2.3: The distribution of modulation relative to the mean fundamental frequency, calculated every 6.4 ms for the duration of each vocalisation. Modulation greater than 10% around the mean fundamental frequency is rare.

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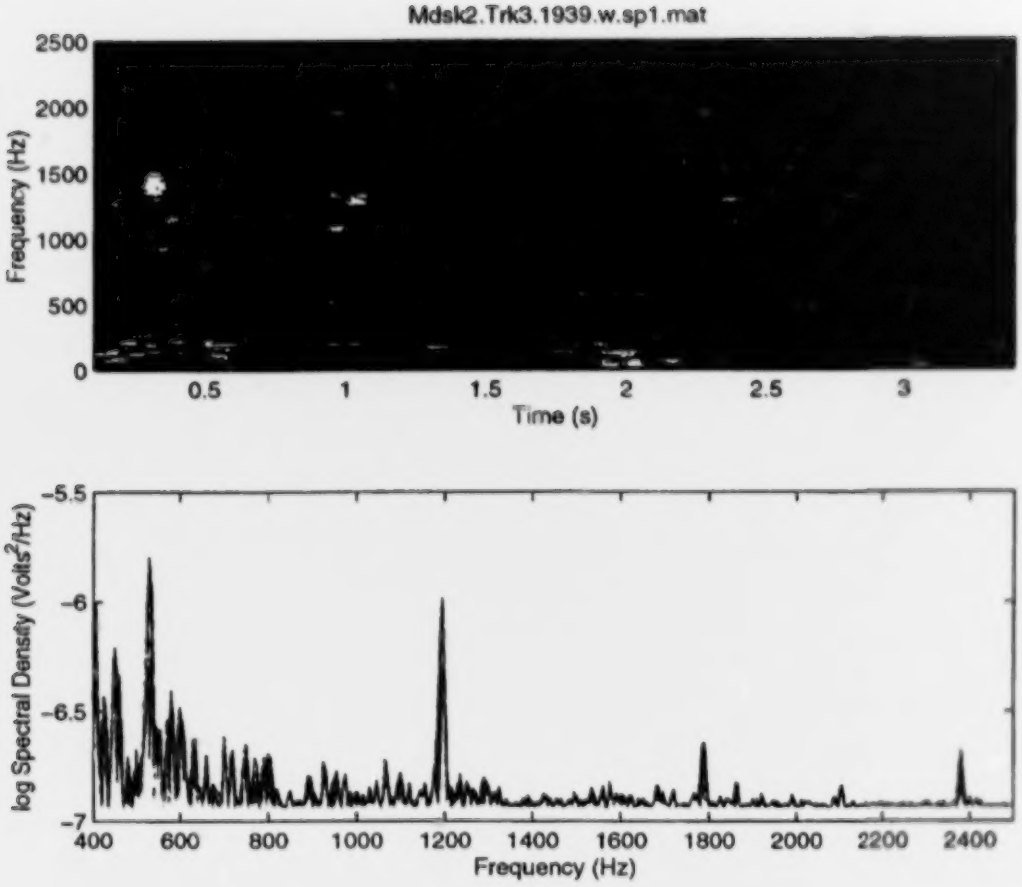

Figure 3.3.1: Spectrogram (above) and the corresponding spectrum (below) for a right whale vocalisation containing harmonics. The spectrogram depicts two vocalisations; each of which have the 2^{nd}, 3^{rd} and 4^{th} harmonics. The spectrum represents the first vocalisation in the spectrogram. The harmonic peaks of the vocalisation included the 2^{nd} harmonic at ≈ 1200 Hz, the 3^{rd} at ≈ 1800 Hz and the 4^{th} at ≈ 2400 Hz. The different colours in the spectrum represent different time bins (6.4 ms) used to create the spectrum.

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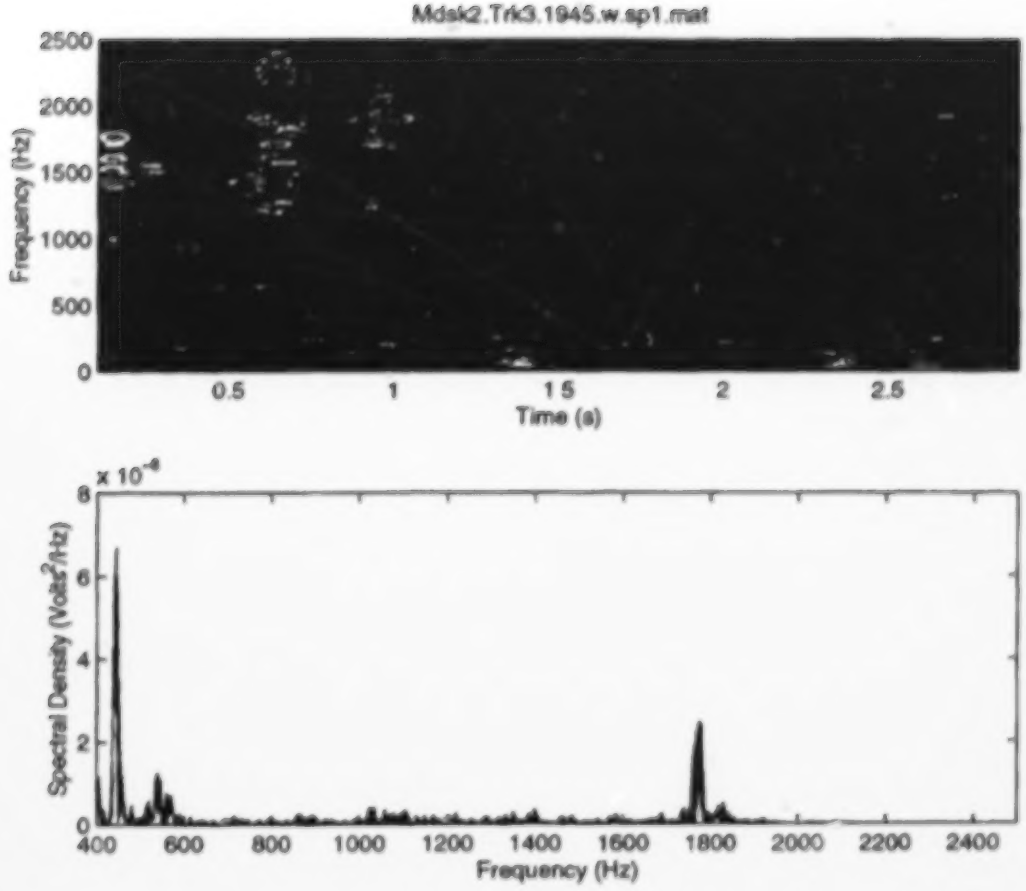

Figure 3.3.2: Spectrogram (above) and the corresponding spectrum (below) for a right whale vocalisation containing a non-harmonic frequency band. This vocalisation has a mean fundamental frequency of 433 Hz and a non-harmonic frequency band at ≈ 1800 Hz. The different colours in the spectrum represent different time bins (6.4 ms) used to create the spectrum.

3 4 Duration

The duration of a vocalisation was defined as the interval between the vocalisation's signal rising above and falling below the ambient noise level (Figure 2.3 2). Using this definition a vocalisation could be separated into more than one part (see above) and short vocalisations (< 0.1s) may not have been detected. The duration of the detected vocalisations ranged from 0.08 s to 1.26 s with a mean duration of 0.42 s ± 0.26 s SD (Figure 3.4.1). Vocalisations at lower frequencies (<200 Hz) appear to be shorter in duration; however, these vocalisations are often separated into more than one part due to the relative high noise levels at lower frequencies and therefore may actually be longer.

3.5 Clusters

The time intervals between vocalisations were not random and clustering of events (vocalisations) was observed. The interval between adjacent vocalisation was as short as 2 seconds. Vocalisations m2t31939 a and b are aurally indistinguishable as separate vocalisations, as there is only a 0 2 s interval between them, and are therefore considered as one vocalisation in the clustering analysis. The distribution of the time interval between vocalisations (Figure 3.5.1) also indicates clustering of vocalisations. The time interval between vocalisations was not uniformly spaced through time (using the Greenwood statistic; rejection region: $G_{obs} > Gn$, $10.97 > 2.62$). This large value of G_{obs} indicated highly irregular spacing of events through time, suggesting clusters of events. Specific goodness of fit tests, using maximum likelihood estimates, also indicated that the number of vocalisations in particular time intervals do not comply to the Poisson distribution (p-value << 0.001, Appendix A).

The time-on-track for sequential vocalisations was examined and a step function for duration or intervals between vocalisations was observed (Figure 3.5.2). Steps (longer durations between successive vocalisations) were observed for the 2nd, 7th, 9th and 13th vocalisations. These "steps" represent time gaps of 200 to 400 s, and separate groups that have relatively short durations between successive vocalisations (10 to 50 s). Three

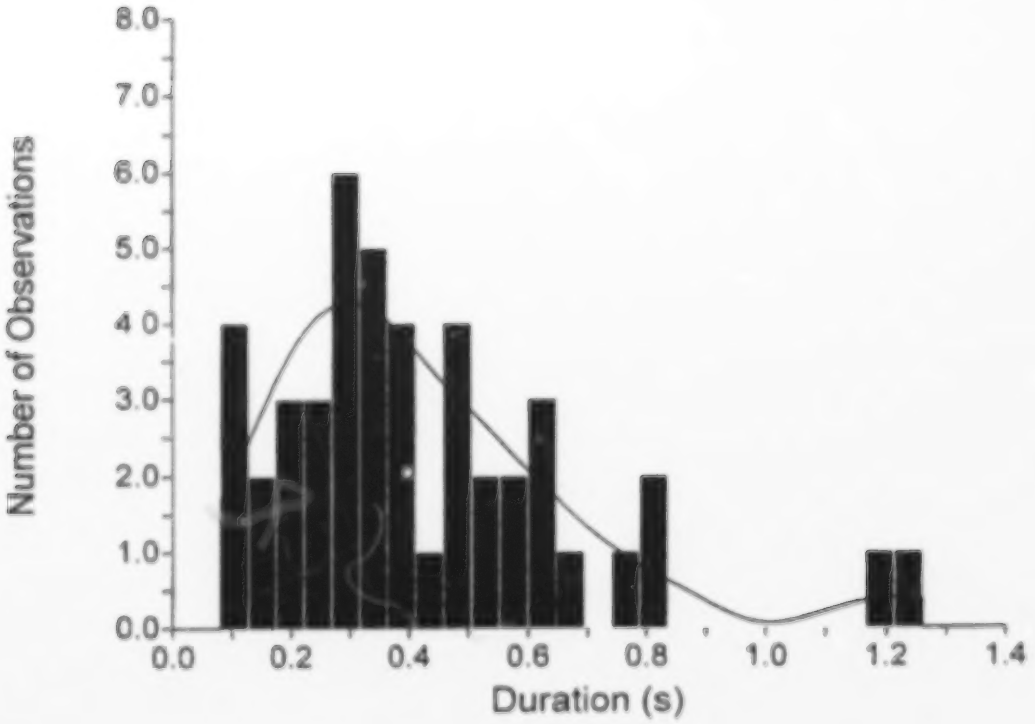

Figure 3.4.1 The distribution of the duration of right whale vocalisations. Durations range in length from 0.08 s to 1.26 s with the mean duration of 0.42 s ± 0.26 s SD The geometric mean of vocalisation duration is 0.35 s.

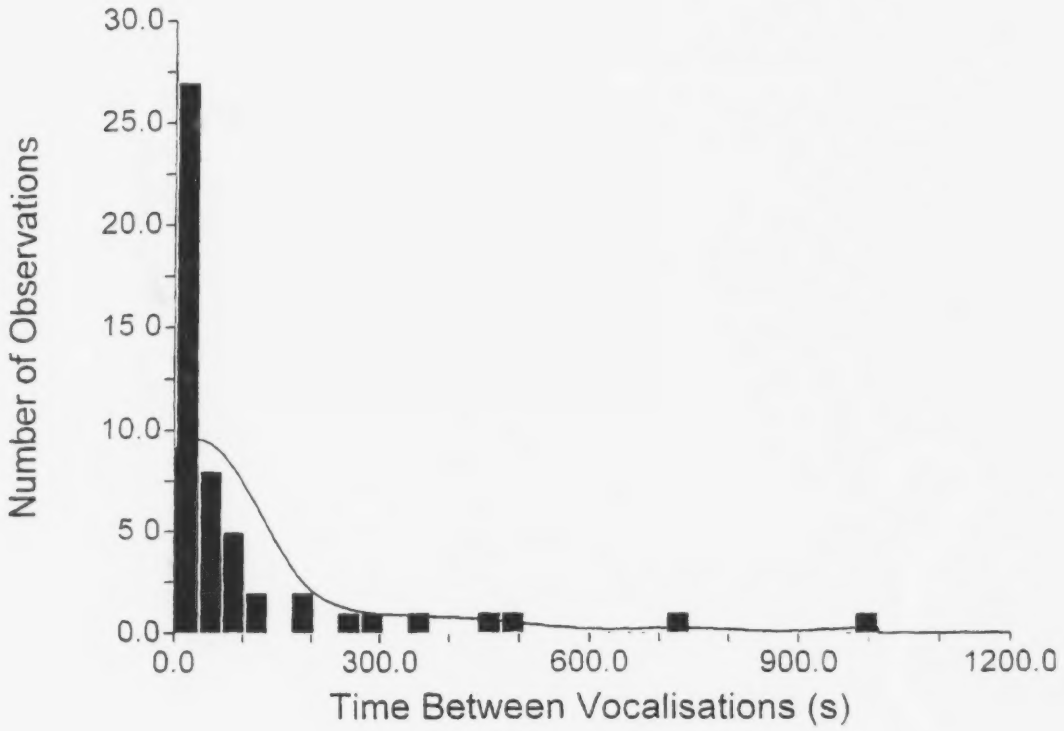

Figure 3.5 1 The distribution of the time between vocalisations, including the time interval between the beginning of the track and the first vocalisation A large number of small intervals between adjacent vocalisations and the presence of longer waiting periods for the next vocalisation (≈ 1000 s) indicate a clustering of vocalisations or events through time

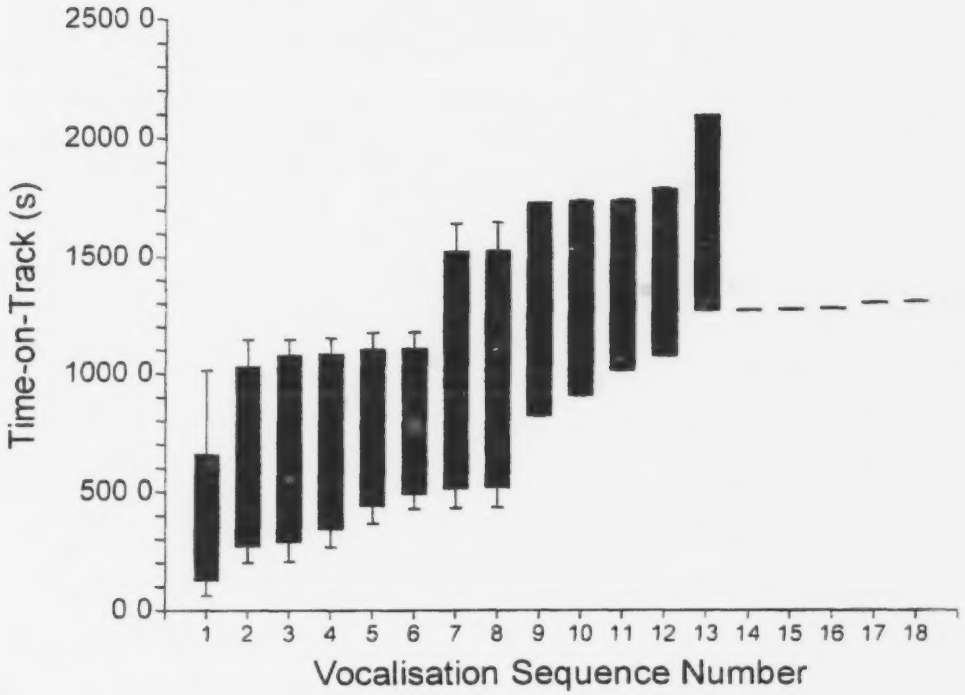

Figure 3.5.2: Box plots of sequential vocalisations and corresponding time-on-track. The step like pattern in the consecutive vocalisations indicates clustering of vocalisations.

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such groups were identified at vocalisations 2 to 6, 7 to 8, 9 to 12 (Figure 3 5 2) These steps indicate pattern of clustering of vocalisations in time. The same step-like pattern was observed when the time to the first vocalisation (t_1) is subtracted from all times on the tracks ($t_i - t_1$ Figure 3.5.3) The median for the 2nd, 3rd, 4th, 5th and 6th vocalisation are very close and there was very little waiting time to the next vocalisation in these 5 vocalisations (Figure 3 5.3). The 7th and 8th vocalisations represent another step, with a very short time to the next vocalisation between the two. Again there is another step which represents the 9th, 10th, 11th, 12th vocalisation on the track. These steps in the time-on-track for sequential vocalisations suggest that there is some pattern or clustering in the time at which vocalisations occur

Simulations were used to investigate clusters further and the results suggest that there is some clustering of events through time To contrast the observed data, a data set was created using an exponential distribution with a mean of 1 vocalisation per minute and a sample size of 20 sequential vocalisations. The exponent in the exponential probability density function (Feller, 1968) was taken to be 60. that is, an average frequency of occurrence of a 1-second vocalisation every 60 seconds. The cumulative sums of the generated numbers were used to reflect a Poisson process. This process was repeated 20 times to simulate several tracks The sequential box plots (Figure 3 5 4) of this simulation do not indicate the step-like pattern seen in the two examples above (Figure 3 5 2 and Figure 3.5.3). The medians of the generated times on track are very similar for sequential vocalisations and although the medians are significantly different from one another (Kruskal-Wallis test on ranks, H_0. all medians are equal, H_a: at least two medians are different, p-value << 0.001), many of the medians for small groups of sequential vocalisations are not significantly different from each other. For example, the median time-on-track for the 11th vocalisation is not significantly different from the time-on-track for vocalisations 8, 9, 10, 12, 13, 14, and 15 (Krustak-Wallis Multiple-Comparison Z Test) The same step-like pattern is not observed with the generated time-on-track, as they tend to increase in a monotonic manner with a rate of 1/60 (Figure 3 5 4). The simulation, the box plot diagrams, as well as the Greenwood statistic all lead to the conclusion that the time interval between vocalisations do not constitute a Poisson process. nor do the time-on-tracks conform to a Poisson distribution (Appendix A)

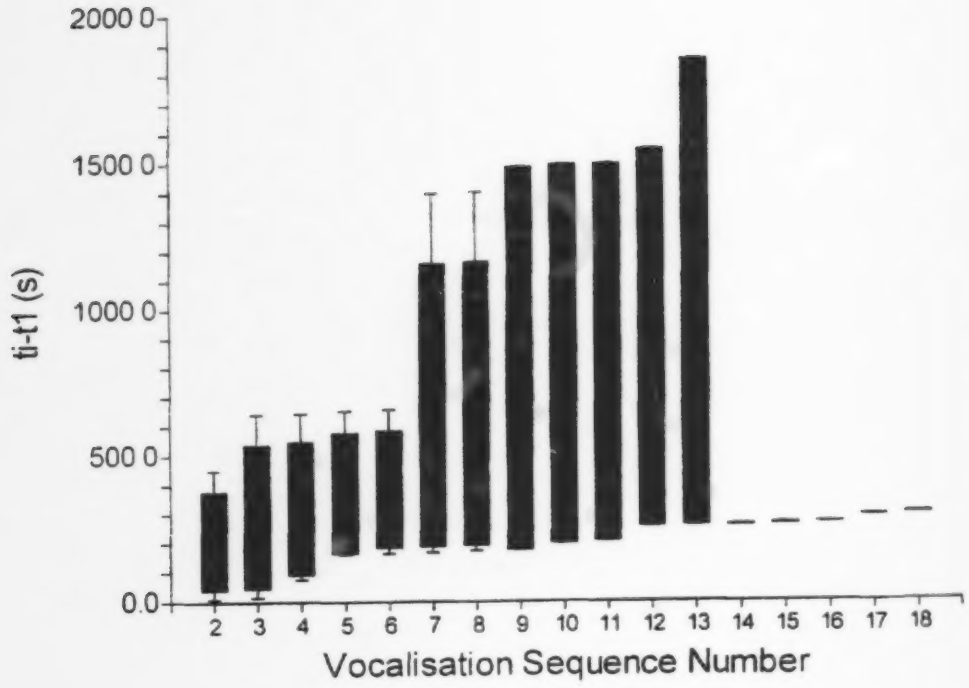

Figure 3.5.3· Box plots of sequential vocalisations with the time to the first vocalisation subtracted from the time on track. A step like pattern for time is seen, denoting the clustering of events (i.e. vocalisations) through time.

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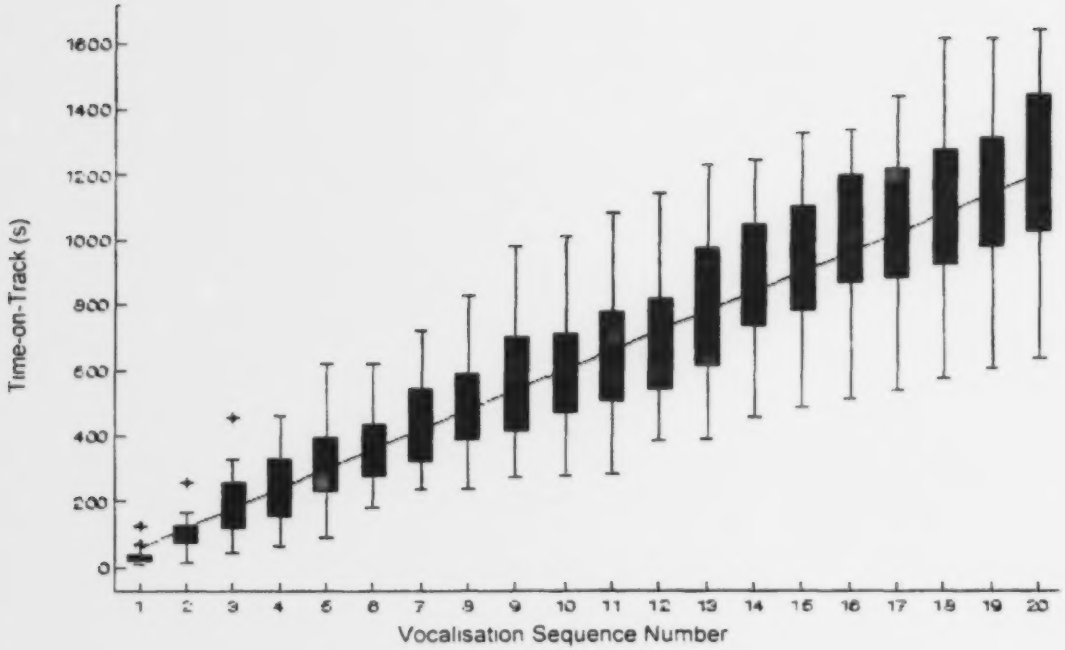

Figure 3.5 4: Box plots of simulated time-on-track, using a Poisson Process (see text for details). There is no indication of clustering of events and the line represents the rate of increase of 1/60 or one vocalisations per minute.

Thus it can be concluded that vocalisations do not occur in a random fashion, nor is the probability of capturing (recording) a vocalisation small.

Clusters were defined as vocalisation occurring within 15 seconds of the previous vocalisation. The 15 s duration was chosen based on the frequency distributions of duration between vocalisation of varying bin widths. Eleven clusters containing 2 to 5 vocalisations per cluster were identified during the 2 hours of recordings.

3 6 Intensity Levels within Clusters

Vocalisations exhibit amplitude modulation as well as frequency modulation. In general, the vocalisations increase in intensity to some maximum and then decrease into the noise floor; however, there are some variations to this pattern of modulation. For example in one vocalisation of 0.6 s duration (m1t72904, Appendix B-Figure B 4) the intensity increased to 400 $Volts^2$, decreased to 85 $Volts^2$, increased to a maximum of 900 $Volts^2$, decreased to 80 $Volts^2$ and then increased again to 500 $Volts^2$ before the intensity decreased to the noise floor.

The intensity levels within clusters were examined to see if there was any evidence to suggest that different whales were vocalising within clusters. The intensity was analysed as a function of time, using clusters where all vocalisations could be examined. The vocalisations of cluster-8 clearly demonstrate that the intensity of one vocalisation (m2t31939b) was much higher relative to the others in the cluster (Figure 3 6.1). This vocalisation had an intensity that was ~ 5X greater than the adjacent vocalisation and ~ 2 orders of magnitude greater that the vocalisation with the lowest intensity (m2t31948). Cluster-3 and -11 show similar results with large changes in intensity between vocalisations separated by 2 and 6 seconds (Appendix B-Figures B.2 and B 4). Other clusters (Appendix B-Figures B.1 and B.3) exhibited little difference in intensity levels among vocalisations.

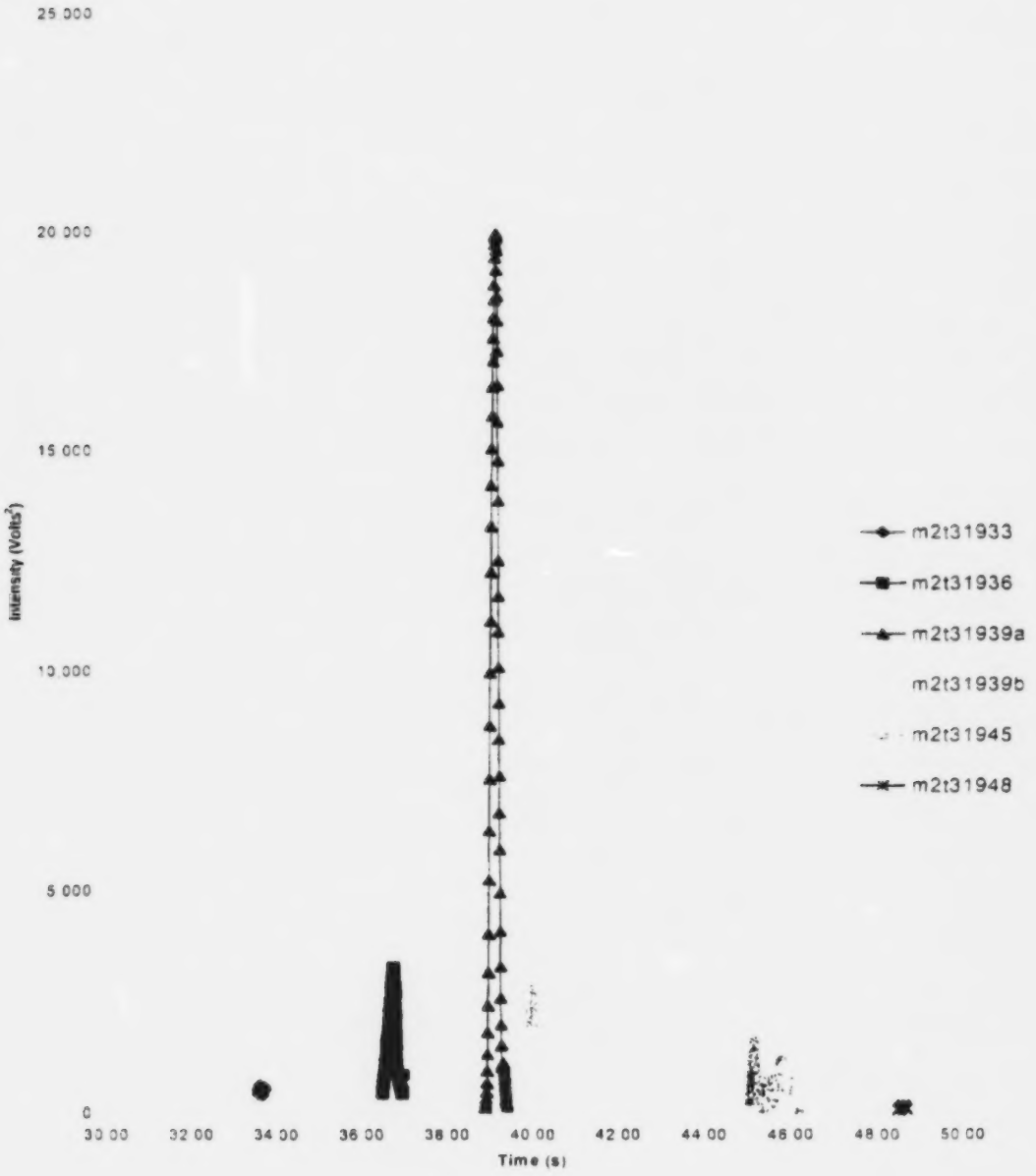

Figure 3.6.1: Intensity of each vocalisation in Cluster 8. Vocalisations are amplitude modulated and there are also amplitude modulations between vocalisations.

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4. DISCUSSION

The results presented here indicate that North Atlantic right whales make various underwater sounds that are detectable and quantifiable. The range of the fundamental frequencies observed is quite large; however, all but a few of the vocalisations were in a limited frequency band ranging from 340 to 600 Hz. The relative frequency modulation was small with ± 20% representing the greatest observed sweep relative to the mean fundamental. The large number of vocalisations recorded over a short time (0.56 vocalisations per minute on average) suggests that right whales are vocalising with sufficient frequency of occurrence to be statistically useful. Thus, there is evidence that the vocalisations of the North Atlantic right whale can be used for locating whales in an acoustical array and thereby used as an early warning system.

4.1 The fundamental frequency and frequency modulation

The majority of the vocalisations analysed occur within a narrow frequency range of 340 to 600 Hz (Figure 3.1.1) and the vocalisations generally have minor modulations relative to the fundamental frequency. This narrow range in fundamental frequencies suggests that vocalisation detection may be relatively simple. If the frequency band that the right whales are using is generally narrow then automated detection of the "proper" signal and the elimination of noise or vocalisations from other species' become less complicated. A specific frequency band, perhaps 300 to 600 Hz, can be the focus for primary monitoring and can be used for locating the majority of the vocalising population within the Bay of Fundy.

If the above small frequency range can be used as a primary screen of acoustic signals, it may be additionally feasible to secondarily screen the information provided by examining the expected modulation relative to the mean fundamental frequency. The 95% confidence interval for the relative modulation can act as a predeterminant to isolate vocalisations from the ambient noise in an early warning system. For example, if a vocalisation was detected with a fundamental frequency of 500 Hz, there is a 95% probably that the modulation relative to the fundamental should be between 459 and 523

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Hz Thus it may be possible to further distinguish the vocalisations from noise and may provide confidence in the nature of the vocalisation by using such a statistic.

4.2 Duration

The estimates of duration are an important characteristic of vocalisations and may also be of use in an early warning system for the detection of North Atlantic right whale. The Bay of Fundy is a high traffic area, with recreational, fishing, and industrial traffic. Within the recordings examined, there was evidence of boat motors, echolocation clicks (presumably from Harbour porpoises), and a known recording of a hand held-foghorn. Give the number and variety of other sounds, a particular signal of unknown origin in the right whale frequency range could be mistaken for a right whale vocalisation. However, if such a signal has a duration that deviates by several standard deviations from the expected, then the probability of its originating from a right whale can be directly assessed

The durations estimated in this study may be shorter than the actual vocalisations due to the effects of noise and the actual distribution may actually be shifted to longer durations with a slightly higher mean Although visual estimates were used to determine the start and stop times of vocalisations, and the mean duration was slightly higher at 0 60 s. the excessively high noise levels still renders negative effects (i.e. reduced mean) on duration estimates.

Noise was a factor in this analysis. Nevertheless, the majority of the vocalisations could be extracted with little effect from ambient and mechanical noise. The duration estimates were largely affected by noise level, compromising the duration measurements as well as mean fundamental frequency calculations as part of some vocalisations were masked by noise that was not included in the analysis. The majority of the noise was caused by the deployment method for the hydrophone and with improved methods of deployment many of the problems and effects of noise will be eliminated.

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4.3 The question of numbers

A high proportion, 74% (39/53) of the vocalisations were sufficiently useful for analysis. The low intensity levels of the remainder, or their association with high noise levels can be attributed to either the whales being out of the range of the hydrophone or the vocalisations were masked by mechanical noise caused by the hydrophone deployment method. However, despite these limitations, during the two hours of data collection in this study, North Atlantic right whale vocalisations were identified at a rate between 0. 3 to 0.7 per minute. If this "n-limited" estimate is extrapolated over a one-month period, our analysis indicates between 14,000 to 30,000 vocalisations per month could be available for monitoring right whales in the Bay of Fundy Assuming a conservative 75% success rate in detecting and quantifying the vocalisations over and above the noise background, there still remains an estimated 10,500 to 22,500 vocalisations per month

It is possible that variation in the intensity of vocalisations within clusters indicates that more than one whale is vocalising Striking differences in intensities of adjacent vocalisations have been interpreted as several whales vocalising at different distances from the hydrophone (Payne and Payne, 1971). Groups of vocalisations in Southern right whales were noted as having roughly equal intensities with as many as 15 vocalisations per minute and these groups were attributed to one whale (Payne and Payne, 1971). The results reported here show that the intensity levels are quite variable within some of the clusters analysed. Given these observed differences in vocalisation intensity of up to two orders of magnitude, and the assumption that call-to-call intensity variations for individual animals do not span such a wide dynamic range (see the literature cited above), it would then follow necessarily that these vocalisations were from different animals. This line of argument admits the hypothesis that individual right whales vocalise at nearly constant intensity levels among vocalisations, and this hypothesis can be tested using data from an on-whale hydrophone (see below and Johnson *et al.*, 1999). If true, then the clusters would have to be due either to vocalisations from widely separated animals vocalising at about the same intensity, or to vocalisations from more closely spaced animals vocalising at much different intensities.

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These alternative explanations have important implications for the interpretation of hydrophone array data in terms of whale numbers, and for array design. It might be possible to determine which of the alternatives is correct by using the sonobuoy array data to identify calls from widely separated animals, and by using on-whale recordings from different whales.

4 4 Multifrequency Vocalisations and Harmonic structure

The intensity levels for many of the vocalisations recorded were very low, possibly indicating the whales were at some distance from the hydrophone. Of the five vocalisations with the greatest intensity levels (m2t3-1939a, m2t3-2019, m2t3-2123, m2t3-2148, m2t3-2154, Table 3 1), only two exhibited harmonics. Considering that only 18% of the vocalisation contained harmonics, and of the vocalisations with strong intensities (< 15,000 Volts^2) only 40 % (2/5) contained harmonics, the presence or absence of harmonic structure may be an expendable characteristic for monitoring purposes

The presence of non-harmonic composition within vocalisations may also be an expendable characteristic for monitoring purposes, as one explanation for their presence is that these non-harmonic frequency bands are actually harmonics. These frequency bands may be higher harmonics, possibly the 4th harmonic, and the lower harmonics, the 2nd and 3rd were not observed. Two non-harmonic frequency bands were noted for vocalisation m1t7-2855, the first of which was at ≈1400 Hz and the second at ≈ 1900 This vocalisation had a mean fundamental frequency of 484 Hz, implying the 3rd harmonic would have a frequency of 1458 Hz and the 4th harmonic a frequency of 1944 Hz, which is the same range for the estimates of the non-harmonic frequency bands. Similar patterns are observed in other vocalisations containing non-harmonic frequency bands, m1t7-2727 has a fundamental frequency of 486 Hz and also contains a non-harmonic frequency band at approximately 2000 Hz. This is approximately the same as the calculated 4th harmonic with a frequency of 1944 Hz. The same patterns are seen in the other vocalisations that contain non-harmonic bands, when each harmonic band in calculated from the mean fundamental frequency, the estimated non-harmonic band falls

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in close proximity to either the 3rd or 4th harmonic calculated from the mean fundamental frequency.

Two explanations that may account for missing harmonics are the noise levels at specific frequency band or the intensity levels of the harmonics. Noise, caused by the deployment method of the hydrophone, may be at the same frequency as lower harmonics and due to these high noise levels in the appropriate frequency range the harmonic structure of a vocalisation may have been masked by this noise.

Intermediate harmonics may have also been missed due to the energy levels at the source, or frequency dependent sound propagation within the Bay Not every harmonic will have the same energy level as the fundamental frequency, nor will all other harmonic frequency bands have the same energy level as all the harmonics within a vocalisation. For example, if there is a greater amount of energy associated with the fourth harmonic when compared to the second and third harmonics, the second and third harmonic frequency bands' energy not be detectable in the spectral analysis. This, combined with frequency-dependant difference in sound propagation, could account for many of the non-harmonic frequency bands observed in the 9% of the vocalisations and these non-harmonic frequency bands may actually be harmonics of the fundamental frequency

An alternative explanation for the presence of the non-harmonic frequency bands is that these higher non-harmonic frequency bands were not generated by the same animal, but originated from another whale vocalising at the same time but at a higher frequency. The non-harmonic frequency band observed in vocalisation m2t3-1945 was in a similar range as the vocalisations with the very high fundamentals (Figure 3.1.4 and Figure 3 3 2) and this would be consistent with the hypothesis that another whale is emitting a vocalisation using a high frequency fundamental. As suggested above, this hypothesis is also testable using the simultaneous airborne recordings from the sonobuoy array collected concomitantly with the hydrophone data. If it can be shown that the non-harmonic frequency bands are generated by the same animal and are part of the harmonic structure of the vocalisation, then they may be a less critical characteristic of the vocalisation for use in vocalisation-based monitoring.

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4.5 Are these vocalisations those of North Atlantic right whales?

The recordings analysed were made in the presence of North Atlantic right whales and a total of nine right whales were identified while recording in the fog, and as many as 60+ where estimated to be resident in the Grand Manan Basin prior to making the recordings. Minke, sei, blue, and humpback whales are also frequently sighted in the Bay of Fundy in August (Power *et al.* 1999). Thus, it is possible that some of the vocalisations recorded and characteristics identified may be attributed to another species. However this is unlikely as the New England Aquarium right whale research team, headed by Philip Hamilton, from Lubec, Maine, identified all species observed during the recording period. Of the whales encountered during the day of sampling, the right whale was the only species observed during recordings. Two minke whales were seen prior to reaching the primary right whale habitat. However these animals were at some distance from recording locations (nominally 22 and 34 km) and their sighting times do not correspond to any recording times.

Spectral comparisons were also conducted to corroborate *in-situ* recordings with known right whale vocalisations (Figure 4.5.1). Johnson, Nowacek and Tyack from the Woods Hole Oceanographic Institute (WHOI, Johnson et al., 1999) provided recordings from an on-whale hydrophone also deployed in the Bay of Fundy. The fundamental frequencies from the on-whale hydrophone were in the same frequency range as the majority of the *in-situ* hydrophone recordings and they also reveal very similar harmonic structure (Figure 4.5.1). There were also low frequency vocalisations recorded with the on-whale hydrophone comparable to the ones observed in the *in-situ* hydrophone recordings. The durations (using our definition) were slightly longer for the on-whale hydrophone with a mean of 0.72 s ± 0.06 SD, which is consistent with the suggestion that the durations in this study were underestimated.

The spectral density of the harmonics from the *in-situ* hydrophone decreases in a log-linear fashion with the higher integer multiples of the fundamental (Figure 4.5.1). The

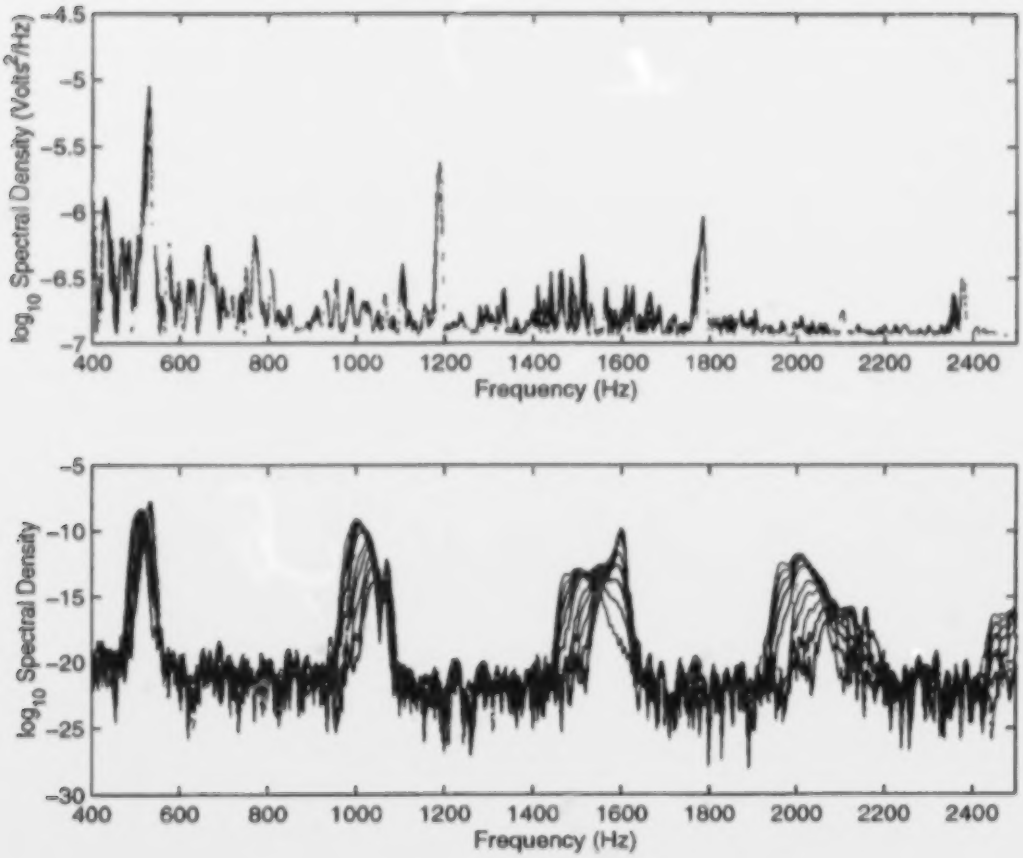

Figure 4.5.1: Spectra of vocalisations recorded by *in-situ* hydrophone (above) in the presence of right whales, and (below) a vocalisation recorded by an on-whale (known right whale individual) hydrophone. The different colours in the spectrum represent different time bins (6 4 ms) used to create the spectrum.

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spectral density of the fundamental frequency from the *in-situ* hydrophone recording was 10X greater than that of the second harmonic and overall the spectral density decreases exponentially. At this stage, it is not clear whether this decrease of spectral density in the higher frequency harmonics is associated with differences in vocalisation propagation or generation.

The results reported in the study also correspond to the original analogue recording physically published by Schevill and Watkins (1962), where the vocalisation presented had a fundamental frequency of approximately 400 Hz. Simple frequency-modulated upsweeps with most energy between 80-250 Hz have been noted by Clark (1999) as contact calls for North Atlantic right whales Our analyses did not reveal any vocalisations that match Clark's However, there were high noise levels below 200 Hz, and unless the vocalisations were very intense these high noise levels (attributed to hydrophone deployment methods alone) would have masked them.

The higher fundamental frequency vocalisations (<900 Hz) observed in the data (6 7%) also seem to have been made by right whales. Southern right whales have been noted to use a principle range of 50 to 500 Hz but also exhibit vocalisations with a fundamental as high as 1500 Hz (Payne and Payne, 1971). It is also possible that these vocalisations with higher frequencies may not be the fundamental frequency, but rather a higher harmonic and the fundamental and lower harmonics may not be detected. Whether these higher vocalisations are harmonics or fundamentals they are still part of the possible range of a North Atlantic right whale. A comparison of the on-whale hydrophone with the historical data substantiates the conclusion that vocalisations from this study are those of the North Atlantic right whale.

4.6 Additional information provided by vocalisations

Clark (1982, 1983) characterised the Southern right whale acoustical repertoire and related six different types to behaviour and activity. Vocalising females in surface-active groups (SAGs) are characterised as producing "raucous complex sounds" (Clark, 1999). "Contact calls" are characterised as low frequency upsweeps (Spero, 1981, Clark

1999) for the North Atlantic right whale. As with the Southern right whales, some of the vocalisations for the Northern right whales may be related to the behaviour of the animals If so, then an early warning system may provide additional information over and above simply the location and distribution of the right whales If the vocalisations can be related to the behaviour of the animals, then behavioural activity of the whales can be monitored using the acoustical array The clustering of vocalisations witnessed in this study may be connected with SAGs The intercall interval (greatest intercall interval is 9.28 s, Kraus, 1991) for this phenomenon is similar to, but slightly less than the 15 second estimate for the time between vocalisations that defined a cluster in this study. The low frequency, upsweeping contact calls could be used as an index of the whale distribution as this type of call has bee attributed to lone animals (Spero, 1980). Comparisons with the Southern right whale data are a logical starting place. Using an acoustical array concomitant with behavioural observations would be invaluable.

It may be possible to decrease fishing gear conflicts by linking vocalisations to the behaviour of the animals. If there are signatures in the vocalisations for specific behavioural activities such as surface active groups, then the overlapping of right whale activity and fishing gear can be eliminated. The location of such groups can be relayed to fishing communities and areas of high right whale activity can be avoided. By reducing the overlapping areas used by the fishing community and right whales, the risk of entanglement is reduced for right whales, and the chance of losing gear is also decreased. New technologies in commercial fishing gear is directed to reduce the likelihood of entanglements (Salvador, 1999) and the acoustical monitoring of right whales may also diminish fishing gear and right whale conflicts at a variety of temporal and spatial scales.

Preliminary findings from a digital acoustic recording tag indicate the North Atlantic right whales are vocalising at the surface, either immediately prior to sounding or immediately subsequent to surfacing (Johnson *et al.*, 1999, Right Whale Consortium Meeting) The depth at which North Atlantic right whales are vocalising has implications in the placement of the hydrophones in the water column, as interpretative problems could occur that are related to the sound propagation of the vocalisations. The deepest part of the Grand Manan Basin is approximately 200 m (Figure 2.1.1) and the steep underwater cliffs will effect the propagation of vocalisations. The source level of the

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vocalisations thus becomes crucial to determine the employment of an acoustical monitoring system.

4.7 Source Levels

The source level (re: 1μPa, 1 m) for vocalisations is the absent but essential component for an early warning system based on an acoustic array moored in the local right whale habitat Source levels are required to determine if the vocalisations will travel a sufficient distance to be detected on more than one hydrophone deployed in the right whale habitat. It will also help determine the optimum distance between hydrophones. Source levels in many studies are back calculated (Watkins and Schevill, 1972, Thompson *et al.*, 1986) using the distance to the known source, the received sound levels, and known hydrophone sensitivities. In this study the source levels could not be calculated because there was no measure of distance to sources and the one opportunity to estimate a source level was missed. When a right whale surfaced and vocalised (extremely loud aurally) at a distance of 5 to 8 metres from the hydrophone, the minidisk stopped due to a full disk Further studies are required to ascertain the source levels required for the implementation of an acoustic array for monitoring, and the sonobuoy array data mentioned above may provide some of these preliminary estimates.

4.8 Summary

North Atlantic right whales are vocal animals that produce sounds ranging from 65 to 2000 Hz, with the majority of vocalisations below 600 Hz. The fundamental frequency, frequency modulation relative to the mean fundamental, and duration are important characteristics and this study provides critical data and statistics that can be applied to detection using an acoustical array. Harmonics and non-harmonic frequency bands are present in some vocalisations though it initially appears that these characteristics are not essential in the implementation of an early warning system Associating behaviour with vocalisation may provide further information when monitoring whales acoustically The declining population of North Atlantic right whales,

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which have an estimated extinction time ≈ 200 years, requires reduced mortality rates to evade extinction. The evidence from this study suggests that the acoustical monitoring of right whales using their vocalisations is possible and thereby an early warning system to decrease fishing gear conflicts and the probability of ship collisions may be a feasible way to directly reduce the man-made mortality.

APPENDIX A: Poisson Distributions

Using varying window widths the observed number of vocalisations within a specific time interval was compared with the expected number of vocalisations based on a Poisson distribution. The recordings of North Atlantic right whale vocalisations were observed during $N = 74$ time intervals of 90 seconds each; the number of vocalisations was obtained for each period. Table A.1 inventories the number of periods (N_k) with exactly k vocalisations. The expected or theoretical values N_p(k; 0.7027) are significantly different (Table A.1, Figure A.1) from the observed values (p-value << 0.001).

Table A.1: Number of vocalisations with a varying window width and their corresponding averages to calculate the theoretical or expected values based on a Poisson distribution.

	Time Interval (Window Width)					
	90 seconds		180 seconds		270 seconds	
k	N_k	$Np(k,0.7027)$	N_k	$Np(k,1.4054)$	N_k	$N_p(k,2.3043)$
0	51	3.665E+01	19	9 075E+00	9	2.296E+00
1	11	2 575E+01	8	1.275E+01	6	5.291E+00
2	5	9.048E+00	1	8.962E+00	0	6.096E+00
3	3	2.119E+00	5	4.198E+00	1	4.682E+00
4	2	3 723E-01	1	1.475E+00	4	2.697E+00
5	0	5.233E-02	0	4.146E-01	1	1.243E+00
6	0	6.128E-03	1	9.712E-02	1	4 774E-01
7	2	6.152E-04	1	1.950E-02	0	1.572E-01
8	0	5.404E-05	0	3.425E-03	0	4.527E-02
9	0	4.219E-06	0	5.349E-04	0	1.159E-02
10	0	2.965E-07	1	7.518E-05	0	2.671E-03
11	0	1.894E-08	0	9.605E-06	0	5.595E-04
12	0	1.109E-09	0	1 125E-06	0	1 074E-04
13	0	5.995E-11	0	1.216E-07	0	1.905E-05
14	0	3.009E-12	0	1.221E-08	0	3.135E-06
15	0	1.410E-13	0	1.144E-09	0	4.816E-07
16	0	6.191E-15	0	1.005E-10	0	6.936E-08
17	0	2.559E-16	0	8.306E-12	1	9.402E-09
18	0	9 990E-18	0	6.485E-13	0	1.204E-09
19	0	3 695E-19	0	4 797E-14	0	1.460E-10
20	0	1.298E-20	0	3.371E-15	0	1.682E-11

By doubling the window width or time interval in which the number of observed vocalisations are counted, the observed values of the vocalisations are also significantly

different from the expected number of vocalisations (based on the Poisson distribution) within 180 second time interval (p-value << 0 001, Figure A 1-B). The lack of fit is clearly demonstrated with the number of 180 s time intervals containing 0 vocalisations From the Poisson distribution, it is expected that there is 9 intervals containing 0 vocalisations, this is considerably lower than the 19 180 s intervals observed that contained 0 vocalisations. With an increased window width the observed data still does not exhibit the properties of a Poisson distribution.

Using a window width of 270 seconds or 4.5 minutes the observed number of vocalisations within the window are significantly different from the expected counts of vocalisations (p-value <<0.001, Figure A.1-C). Using the generated expected numbers the highest frequency of occurrence transpires at k=2 In the data there are no 180 s intervals that have two vocalisations within them. There are also a higher number of intervals with no vocalisations in the observed data when compared to the expected number on intervals with no vocalisations in them. The probability of observing more than 10 vocalisation in an interval is extremely low, and the probability of observing 17 vocalisations in 4 5 minutes is 4 09E-10. however, this does occur on minidisk 2 track 7 By further increasing the window width the observed data still does not conform to the Poisson distribution.

The goodness of fit test for a Poisson distribution was rejected at all four window widths or time intervals. If the probably of an event, in this case a North Atlantic right whale vocalisation, was small and occurred randomly, one would suspect that the distribution of events would be Poisson This data clearly demonstrates that the occurrence of vocalisations does not follow a Poisson distribution and it may also be true that the occurrence of one vocalisation increases the occurrence of another, hence it may be more likely to obtain groups or clusters of vocalisations then single vocalisations.

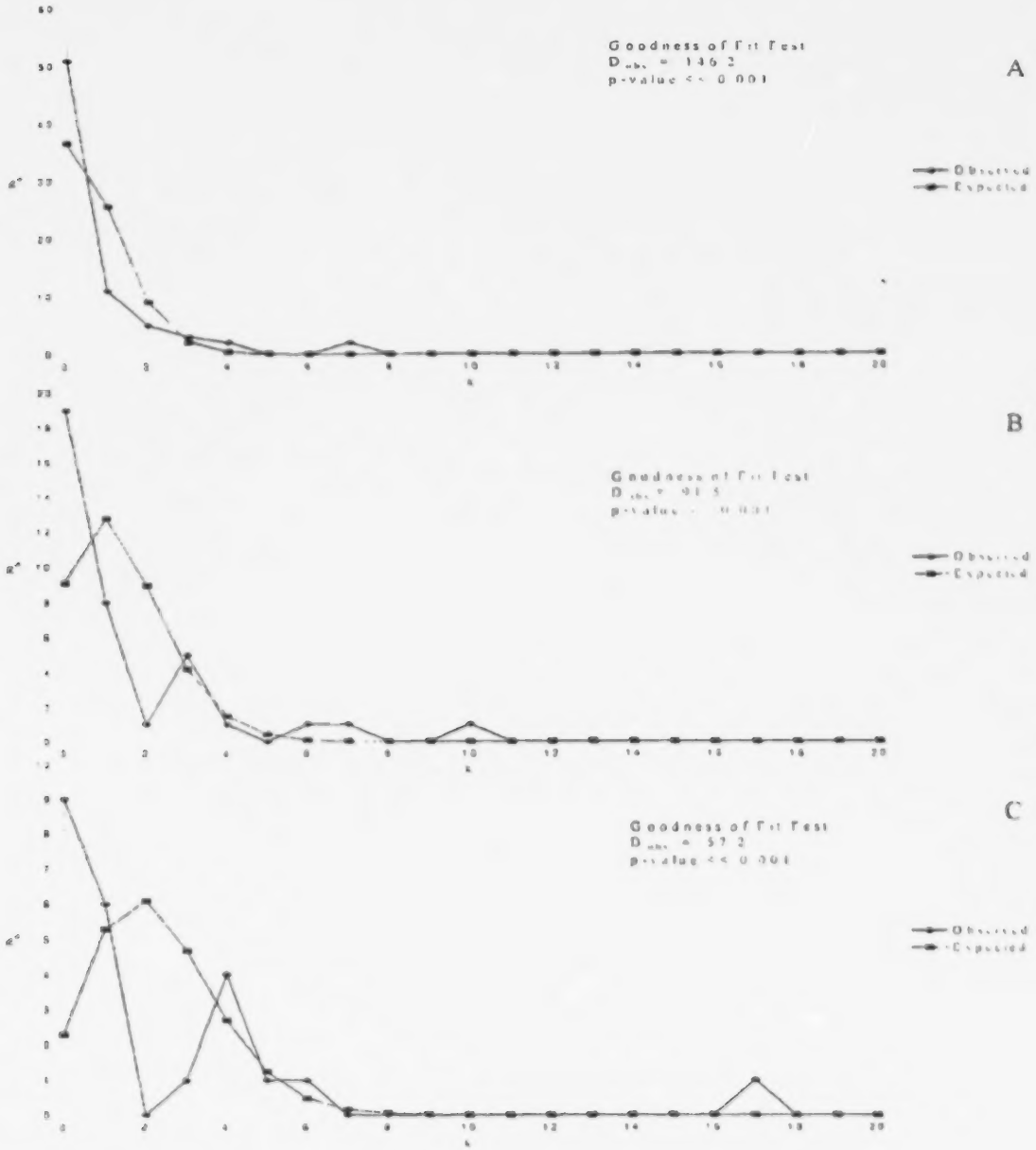

Figure A.1: The number of periods containing varying counts of vocalisations. Both the observed and expected values are plotted; the expected were calculated using a Poisson distribution. Numbers were obtained using time intervals of A) 90 s, B) 180 s, and C) 270 s.

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APPENDIX B Intensity within Clusters

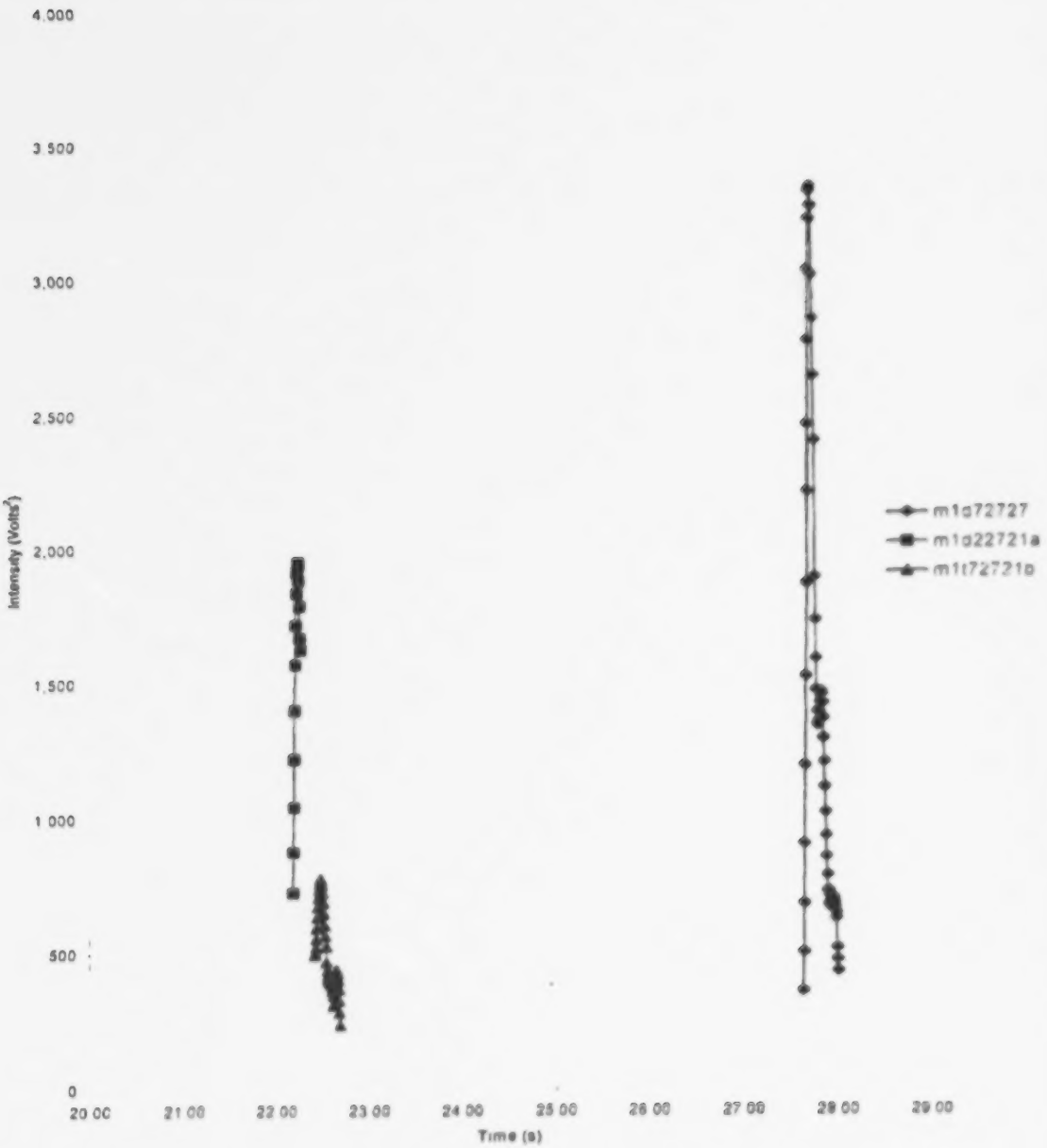

Figure B 1: Intensity of each vocalisation in Cluster 2. Vocalisations are amplitude modulated and there are also amplitude modulations between vocalisations.

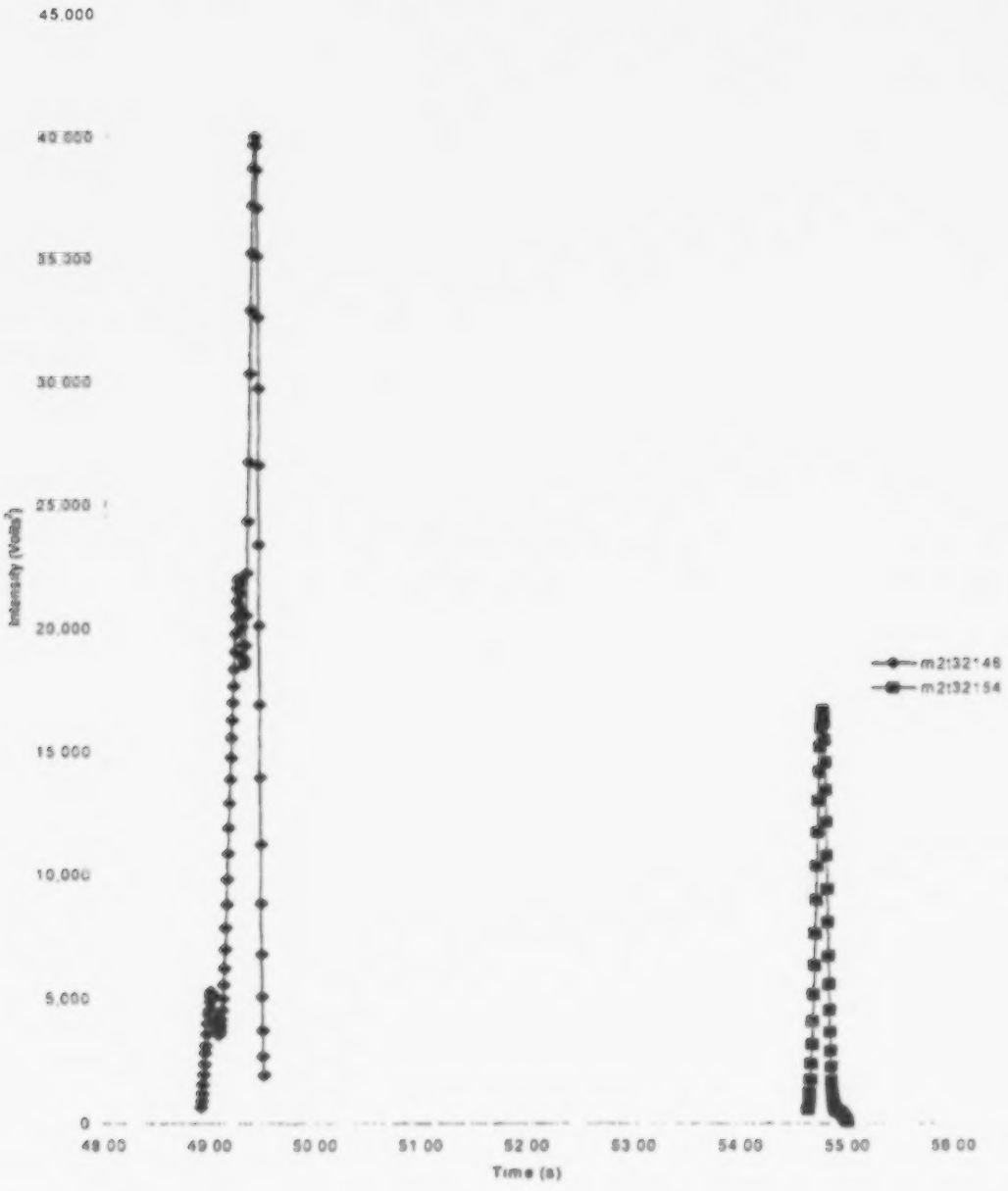

Figure B.2: Intensity of each vocalisation in Cluster 11. Vocalisations are amplitude modulated and there are also amplitude modulations between vocalisations.

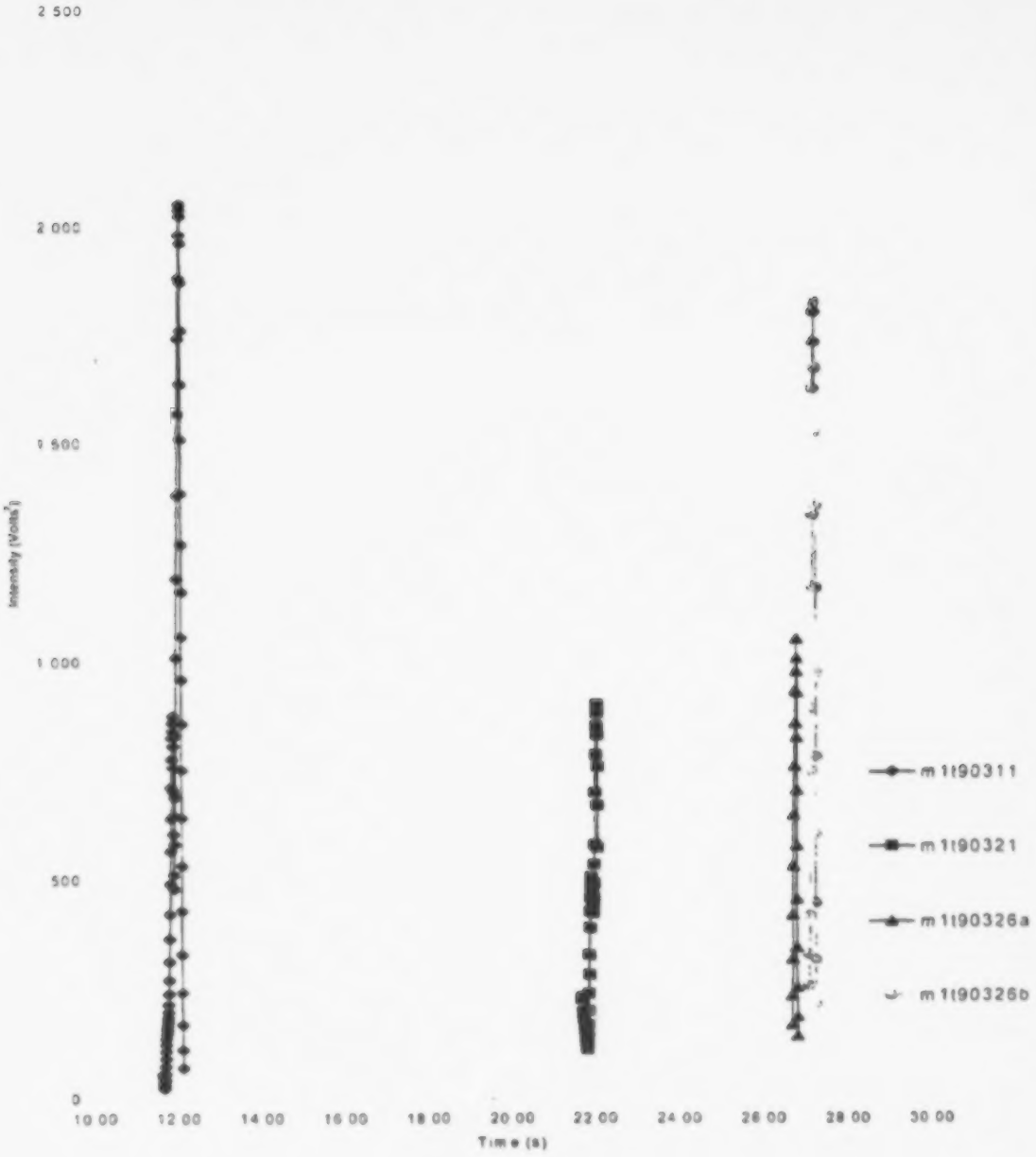

Figure B.3: Intensity of each vocalisation in Cluster 4. Vocalisations are amplitude modulated and there are also amplitude modulations between vocalisations.

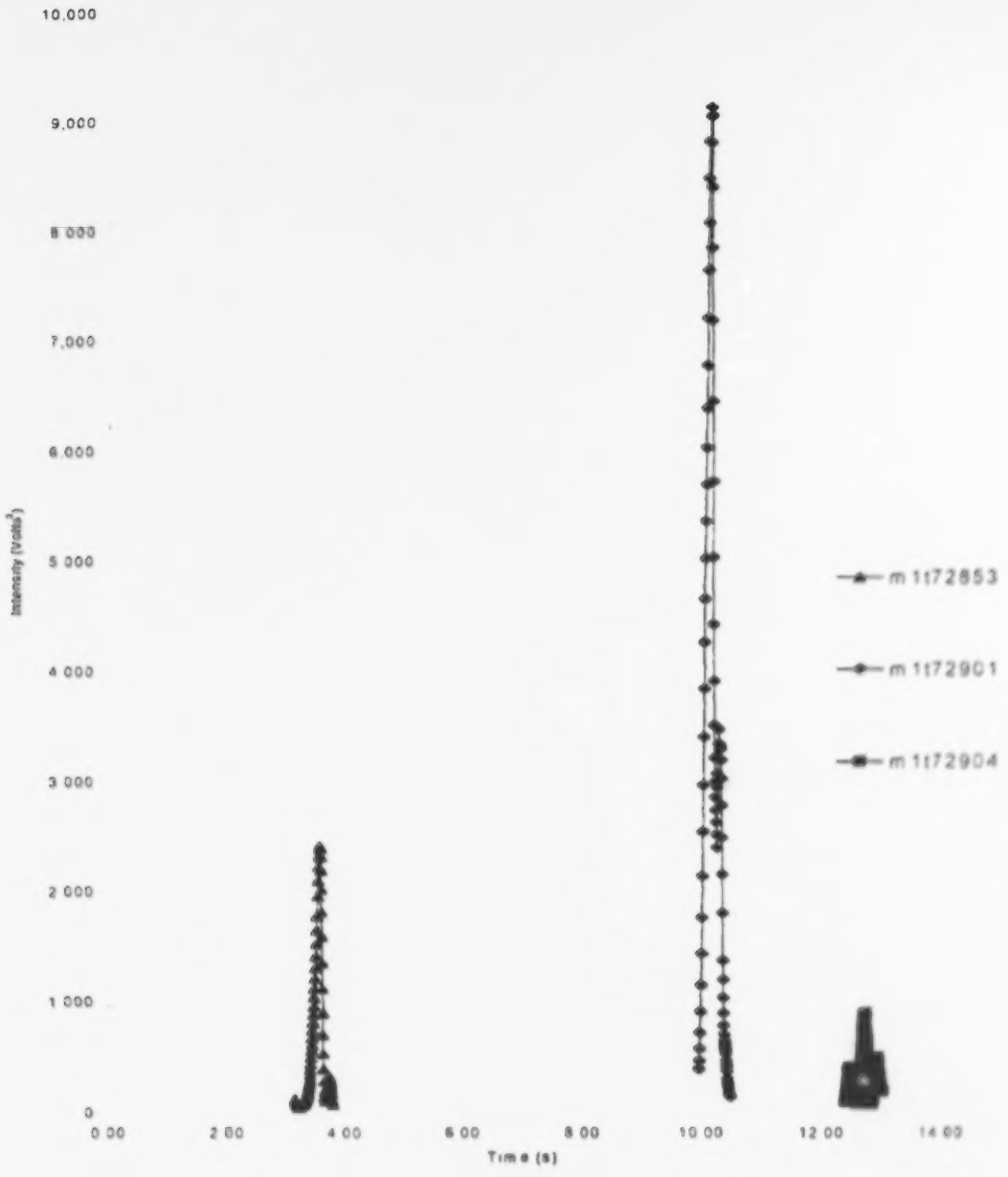

Figure B.4: Intensity of each vocalisation in Cluster 3. Vocalisations are amplitude modulated and there are also amplitude modulations between vocalisations.

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Hydrophone recordings made in the presence of a North Atlantic right whale (*Eubaleana glacialis*) aggregation in July 1999 provide data for part of a pilot study to assess the feasibility of a passive acoustic whale monitoring and locating system. Digitised vocalisations are quantified in the time and frequency domains to classify the vocalisations in terms of frequency, modulation, duration, harmonics, and time between individual vocalisations. The majority of the mean fundamental frequencies range between 340 and 600 Hz and on average the duration of the vocalisations was 0.42 seconds ± 0.26s SD. Right whale vocalisations are frequency and amplitude modulated and a 95% confidence interval for modulation relative to the mean fundamental frequency is [-0.082 0.046]. Harmonics and non-harmonic frequency bands above the fundamental were seen in 27% of the vocalisations and may not be significant characteristics in terms of monitoring. Vocalisations occur at a rate of 0.32 to 0.69 per minute, suggesting that North Atlantic right whales are vocalising sufficiently for monitoring. The vocalisations of North Atlantic right whales contain distinct characteristics that are detectable and can be quantified to allow for automated monitoring of right whales in the Bay of Fundy.

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